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The Removal of Metals and Viruses in Advanced Wastewater Treatment Sequences

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College Station

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by

Steven E. Esmond
Albert C. Petrasek, Jr.
Harold W. Wolf
D. Craig Andrews
Texas A&M University
College Station, Texas 77843

Grant No. S-801026

Project Officer

Irwin Kugelman
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the projects of that research; a most vital communications link between the researcher and the user community.

This report details studies of metals and virus removal in a variety of advanced waste treatment systems.

Francis T. Mayo
Director
Municipal Environmental Research Laboratory

ABSTRACT

An extensive study of metals and virus removals by advanced wastewater treatment processes was conducted in Dallas, Texas from June 1972 through December 1973. Processes applied to a biologically nitrified effluent included chemical coagulation with alum and/or lime, high-pH lime treatment with and without recarbonation, filtration through multi- and dual-media filters, and carbon adsorption. The high-pH lime treatment with recarbonation provided a most effective treatment for both metals removals and disinfection. Boron surfaced as a material that may require other means of control. Although high-pH lime treatment was indicated to be extremely effective for virus removal (or inactivation), metals removal were not of the same order of magnitude. Thus, efforts to control metals at points of discharge are strongly supported. The removal of some metals by biological processes appeared to be influenced by their concentration. Median values were observed to be more indicative of the plant processes than mean values. Coliphages were observed to provide essentially the same virus removals values as polioviruses. The suggestion is made that all wastes should be subject to biological treatment, and if such treatment is found ineffective, then other means of control are warranted.

This report was submitted in fulfillment of Grant No. S-801026 by Dallas Water Utilities under the sponsorship of the U.S. Environmental Protection Agency. Work was performed under subcontract to Texas A&M University. This report covers the period June 1972 to December 1973.

CONTENTS

Foreword iii
Abstract iv
Figures vii
Tables xiii
Acknowledgement xx

1. Introduction. 1
    Background of the Dallas Program 4
    Research Presented in This Report 5
2. Conclusions 6
3. Recommendations 8
4. Description of Research Facilities. 9
    City of Dallas Collection System 9
    Treatment Facilities 12
5. Sampling and Analytical Procedures 32
    Sampling Procedures 32
    Analytical Procedures 33
    Virus Determinations 36
6. High-pH Lime Coagulation 38
    General 38
    Completely-Mixed Activated Sludge System 41
    Upflow Clarifier 46
    Multimedia Filters 49
    Activated Carbon Adsorption System 49
    Metals Removals 53
7. Alum Coagulation 77
    General 77
    Completely-Mixed Activated Sludge System 81
    Upflow Clarifier 87
    Multimedia Filters 87
    Activated Carbon Adsorption Column 92
    Metals Removals 96
8. High-pH Lime Coagulation And Single-Stage Recarbonation . . 119
    General 119
    Completely-Mixed Activated Sludge System 120
    Upflow Clarifier 131
    Singe-Stage Recarbonation 131
    Multimedia Filter 135
    Activated Carbon Adsorption 135
    Metals Removals 139

9. Responses of Individual Metals 166
Biological Treatment 166
The Three Combinations of Treatment Sequences 179
Metals Removal Summary 202
10. Virus Inactivation Study 221
General 221
Results And Discussion of the Virus Runs. 223

FIGURES

Number		Page
1.	Existing City of Dallas water supply network	2
2.	Possible sources of influents for the Pilot Plant at the White Rock Sewage Tratment Plant	16
3.	Dallas Water Reclamation Research Center - Demo Plant	17
4.	Aerial photograph of the Demonstration Plant	18
5.	No. 1 Aeration Basin with Aquarius oxygen transfer equipment	20
6.	Section of the No. 1 Final Clarifier after modifications	22
7.	Elevation of the Upflow Clarifier	24
8.	Typical elevation of the No. 1 and No. 2 gravity filters	27
9.	Media expansion as a function of temperature and backwash rate for the No. 1 Multimedia Filter	30
10.	Elevation of downflow granular activated carbon contactors	31
11.	Process configuration: High-pH lime coagulation without recarbonation June, August-October 1972, November-December 1973	39
12.	Raw Wastewater and product water COD values observed during the high-pH lime coagulation study	42
13.	Effluent nitrogen concentrations observed during the high-pH lime coagulation study	43
14.	Frequency distributions for silver, high-pH lime coagulation study.	59
15.	Frequency distributions for arsenic, high-pH lime coagulation study	61

FIGURES (continued)

Number Page

16. Frequency distributions for barium, high-pH lime coagulation study 62

17. Frequency distributions for cadmium, high-pH lime coagulation study 64

18. Frequency distributions for cobalt, high-pH lime coagulation study 65

19. Frequency distributions for chromium, high-pH lime coagulation study 67

20. Frequency distributions for mercury, high-pH lime coagulation study 69

21. Frequency distributions for molybdenum, high-pH lime coagulation study 71

22. Frequency distributions for nickel, high-pH lime coagulation study 73

23. Frequency distributions for lead, high-pH lime coagulation study 74

24. Frequency distributions for selenium, high-pH lime coagulation study 75

25. Process configuration: Alum coagulation, November, 1972 - October 30, 1973 78

26. Time series plots of sludge age values, and selected NH_3-N and COD concentrations for the alum coagulation study 79

27. Probability distributions for different forms of nitrogen in the activated sludge influent 84

28. Probability distributions for different forms of nitrogen in the upflow clarifier effluent 85

29. Probability distributions for COD and TOC concentrations in the activated sludge influent 86

29a. Frequency distributions for total P and turbidity values in the upflow clarifier effluent 90

FIGURES (continued)

Number Page

30. Frequency distributions for observed nitrogen concentrations in the final product water, alum coagulation study 94

31. Frequency distributions for selected water quality parameters in the final product water, alum coagulation study 95

32. Selected frequency distributions for arsenic, alum coagulation study 103

33. Selected frequency distributions for barium, alum coagulation study 104

34. Selected frequency distributions for cadmium, alum coagulation study 106

35. Frequency distributions for cobalt in sequence influent and effluent, alum coagulation study 107

36. Frequency distributions for chromium, alum coagulation study 108

37. Frequency distributions for mercury, alum coagulation study 111

38. Frequency distributions for molybdenum, alum coagulation study 113

39. Frequency distributions for nickel, alum coagulation study 114

40. Frequency distributions for lead, alum coagulation study 115

41. Frequency distributions for selenium, alum coagulation study 118

42. Process configuration: High-pH lime coagulation and single-stage recarbonation; November 2, 1973 - January 31, 1974 121

43. Frequency distributions for selected COD data; high-pH lime coagulation and recarbonation study 123

FIGURES (continued)

Number Page

44. Frequency distributions for selected TSS data; high-pH lime coagulation and recarbonation study 124

45. Frequency distributions for selected NH_3-N data; high-pH lime coagulation and recarbonation study 128

46. Frequency distributions for selected nitrate-nitrite nitrogen data; high-pH lime coagulation and recarbonation study 129

47. Plot of effluent COD versus effluent TSS for the CMAS system, high-pH lime coagulation and recarbonation study 130

48. Frequency distributions for TOC data; high-pH lime coagulation and recarbonation study 138

49. Frequency distributions for selected color data; high-pH lime coagulation and recarbonation study 140

50. Frequency distributions for selected organic nitrogen data; high-pH lime coagulation and recarbonation study 141

51. Frequency distributions for selected total P data; high-pH lime coagulation and recarbonation study 142

52. Frequency distributions for arsenic, high-pH lime coagulation and recarbonation study 149

53. Frequency distributions for barium, high-pH lime coagulation and recarbonation study 151

54. Frequency distributions for cadmium, high-pH lime coagulation and recarbonation study 153

55. Frequency distributions for cobalt, high-pH lime coagulation and recarbonation study 154

56. Frequency distributions for chromium, high-pH lime coagulation and recarbonation study 155

57. Frequency distributions for mercury, high-pH lime coagulation and recarbonation study 158

FIGURES (continued)

Number | | Page
58. Frequency distributions for nickel, high-pH lime coagulation and recarbonation study 160
59. Frequency distributions for lead, high-pH lime coagulation and recarbonation study 161
60. Frequency distributions for selenium, high-pH lime coagulation and recarbonation study 163
61. Frequency distributions for strontium, high-pH lime coagulation and recarbonation study 164
62. Chromium reductions vs influent concentrations, showing a typical concentration effect: No. 1 activated sludge unit 175
63. Arsenic levels in wastewater after treatment by secondary and tertiary processes 180
64. Barium concentration in wastewater after treatment by secondary and teritary processes 190
65. Cadmium concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 191
66. Chromium concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 192
67. Copper concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 193
68. Iron concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 195
69. Mercury concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 196
70. Manganese concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 197
71. Lead concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 199
72. Selenium concentrations remaining in wastewater after treatment by secondary and tertiary processes . . 200

FIGURES (continued)

Number Page

73. Zinc concentrations remaining in wastewater after treatment by secondary and tertiary processes 201

74. Residence time distribution function for the upflow clarifier 222

75. Influent and effluent virus counts obtained during Virus Run Number One 227

76. Influent virus counts obtained during Virus Run Number Two 231

TABLES

Number		Page
1	Summary of existing water supply for the year 2020 . . .	3
2	Sizes and lengths of gravity mains in the sanitary sewer collection system	10
3	Summary of industrial and commercial discharges to the collection system	11
4	Influent metals concentrations for the fiscal year 1973	13
5	Characteristics of raw wastewater at the White Rock STP for the period of June, 1972 through February 27, 1974 .	14
6	Technical data for the No. 1 aeration basin	19
7	Technical date for the No. 1 final clarifier	23
8	Technical date for the upflow clarifier	25
9	Media specifications for the No. 1 mixed-media filter. .	28
10	Summary of water quality date for the high-pH lime coagulation study	40
11	Performance summary of the completely mixed activated sludge system high-pH lime coagulation study	44
12	Process summary of the completely-mixed activated sludge system, high-pH lime coagulation study	45
13	Process summary for the upflow clarifier, high-pH lime coagulation study	47
14	Performance summary for the upflow clarifier, high-pH lime coagulation study	48
15	Process summary for the multimedia filter, high-pH lime coagulation study	49

TABLES

Number		Page
16	Performance summary for the multimedia filters, high-pH lime coagulation study	50
17	Process summary for the activated carbon adsorption system, high-pH lime coagulation study	51
18	Performance summary for the activated carbon adsorption system, high-pH lime coagulation study	52
19	Activated sludge influent metals summary high-pH lime coagulation study June, August-October 1972, November-December 1973	54
20	Activated sludge effluent metals summary high-pH lime treatment without recarbonation June, August-October 1972. November-December 1973	55
21	Up-flow clarifier effluent metals summary high-pH lime treatment without recarbonation June, August-October 1972, November-December 1973	56
22	Filter effluent metals summary high-pH lime treatment without recarbonation June, August-October 1972, November-December 1973	57
23	Carbon column effluent metals summary high-pH lime treatment without recarbonation June, August-October 1972, November-December 1973	58
24	Overall water treatment summary alum coagulation study	80
25	Performance summary of the completely-mixed activated sludge system, alum coagulation study	82
26	Process control summary for the completely-mixed activated sludge system, alum coagulation study	83
27	Performance summary for the upflow clarifier.alum coagulation study	88
28	Process summary for the upflow clarifier,alum coagulation study	89
29	Performance summary for the multimedia filter, alum coagulation study	91

TABLES

Number Page

30 Performance summary for the activated carbon adsorption column, alum coagulation study 93

31 Activated sludge influent metals summary alum treatment November 1972 - October 1973 97

32 Activated sludge effluent metals summary alum treatment November 1972 - October 1973 98

33 Up-flow clarifier metals summary; alum treatment November 1972 - October 1973 99

34 Filter effluent metals summary alum treatment November 1972 - October 1973 100

35 Carbon column effluent metals - summary alum treatment November 1972 - October 101

36 Summary of water quality data for the high-pH lime coagulation and recarbonation study 122

37 Performance summary of the completely-mixed activated sludge system, high-pH lime coagulation and recarbonation study 125

38 Process summary for the completely-mixed activated sludge system, high-pH lime coagulation and recarbonation study 126

39 Performance summary for the upflow clarifier, high-pH lime coagulation and recarbonation study 132

40 Process summary for the upflow clarifier, high-pH lime coagulation and recarbonation study 133

41 Performance summary for the recarbonation basin, high-pH lime coagulation and recarbonation system 134

42 Performance summary for the No. 1 multimedia filter, high-pH lime coagulation and recarbonation study 136

43 Performance summary for the No. 4 carbon column, high-pH lime coagulation and recarbonation 137

TABLES

Number Page

44 Activated sludge influent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 143

45 Activated sludge effluent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 144

46 Up-flow clarifier effluent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 145

47 Recarbonation basin effluent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 146

48 Filter effluent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 147

49 Carbon column effluent metals summary,high-pH lime treatment with recarbonation November 1973 - January 1974 148

50 Activated sludge influent, June 1972 through January 1974 167

51 Hydraulic and process control for the activated sludge process 169

52 Performance summary, No. 1 activated sludge system . . 170

53 Activated sludge influent metals summary June 1972 - January 1974 171

54 Activated sludge effluent metals summary June 1972 - January 1974 172

55 Analytical data summary high-pH lime treatment without recarbonation June, August-October 1972, November-December 1973 181

56 Analytical data summary alum treatment November 1972 - October 1973 182

TABLES

Number		Page
57	Analytical data summary high-pH lime treatment with recarbonation November 1973 - January 1974	183
58	Summary of mean concentrations, high-pH lime treatment without recarbonation June, August-October 1972, November-December 1973	184
59	Summary of mean concentrations, alum treatment November 1972 - October 1973	185
60	Summary of mean concentrations, high-pH lime treatment with recarbonation November 1973 - January 1974	186
61	Summary of mean train removals	187
62	Summary of median train removals	188
63	Change in mean metals concentrations by chemical treatment	203
64	Percent metals removal by chemical treatment	204
65	Change in mean metals concentrations by filtration	205
66	Percent metals removal by filtration	206
67	Change in mean metals concentrations by chemical treatment and filtration	207
68	Percent metals removal by chemical treatment and filtration	208
69	Summary of metals removal demonstrated by chemical treatment and filtration processes	210
70	Change in mean metal concentration by activated carbon adsorption	211
71	Percent metals removal by activated carbon adsorption	212
72	Change in mean metal concentration and percent removal for the AWT processes	213

TABLES

Number Page

73 Metals concentrations having linear correlation coefficients (r) of 0.80 or greater, high-pH lime treatment without recarbonation 214

74 Metals concentrations having linear correlation coefficients (r) of 0.80 or greater, alum treatment 215

75 Metals concentrations having linear correlation coefficients (r) of 0.80 or greater, high-pH lime treatment with recarbonation 216

76 Percentage of samples exceeding drinking water limits . 218

77 Comparison of observed metals removals 219

78 Metals concentrations in AWT effluents as a percent of the maximum recommended concentration 220

79 Chemical-physical analytical results, Virus Run Number One 224

80 Coliphage results, Virus Run Number One 226

81 Poliovirus results, Virus Run Number One 226

82 Chemical-physical analytical results, Virus Run Number Two 228

83 Coliphage results, Virus Run Number Two 230

84 Poliovirus results, Virus Run Number Two 230

85 Chemical-physical analytical results, Virus Run Number Three 232

86 Coliphage results, Virus Run Number Three 233

87 Poliovirus results, Virus Run Number Three 233

88 Regrowth study results 234

89 Laboratory recarbonation and regrowth study results . . 235

90 Chemical-physical analytical results, Virus Run Number Four 237

TABLES

Number		Page
91	Coliphage results, Virus Run Number Four	238
92	Poliovirus results, Virus Run Number Four	238

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SECTION 1

INTRODUCTION

As shown in Figure 1, the City of Dallas is located in the upper Trinity River watershed of North Central Texas. This region is naturally water deficient, and in fact, there is only one natural lake in the whole State of Texas. In the upper Trinity River basin, average annual precipitation ranges from about 100 cm (40 in.) per year in the eastern portions to 50 cm (20 in.) per year in the western section. In general, average annual precipitation and evaporation rates are about equal, and drought periods in excess of 60 days are not uncommon. These factors combine to make water a very valuable resource in North Central Texas.

The City of Dallas derives its drinking water supply from the extensive reservoir network shown in Figure 1. The water supply is derived from six reservoirs on three watersheds, with estimated safe yields for the year 2020 indicated in Table 1.

During the middle 1950's North Central Texas experienced a protracted drought. The City of Dallas investigated two alternate sources of water to augment its dwindling supply. One was to pump water from the highly mineralized Red River into the existing reservoir system, and the other was to utilize the waters of the West Fork of the Trinity River which carry a considerable amount of pollution from the wastewater effluents of the City of Ft. Worth and the mid-cities between Ft. Worth and Dallas. In 1955 the thought of "drinking someone else's sewage" did not meet with wide acceptance from either the general public or the City Council and the decision was made to import water from the Red River. Consequently, the City survived the drought by utilizing the Red River over a three-year period, but not without effect. It has been estimated that a transient rise in heart-disease related deaths could be attributed to the period when water with a higher sodium content was used (1). A most important point emerging from this period is that as early as 1955 a major American city had seriously evaluated the possibility of an indirect wastewater reuse as an alternative supply of drinking water.

With respect to total water resources management in the upper Trinity River Basin,indirect but intentional wastewater reuse is of considerable importance to the City of Dallas. Both the Bachman and the Elm Fork Purification Plants of the City of Dallas withdraw water from the Elm Fork of the Trinity River. Estimated water supply for the year 2020 includes 329,000 cu m per day (86.8 MGD) from Garza-Little Elm Reservoir, 38,000 cu m per day (10.0 MGD) from Grapevine Reservoir, and 156,000 cu m per day (41.3MGD)

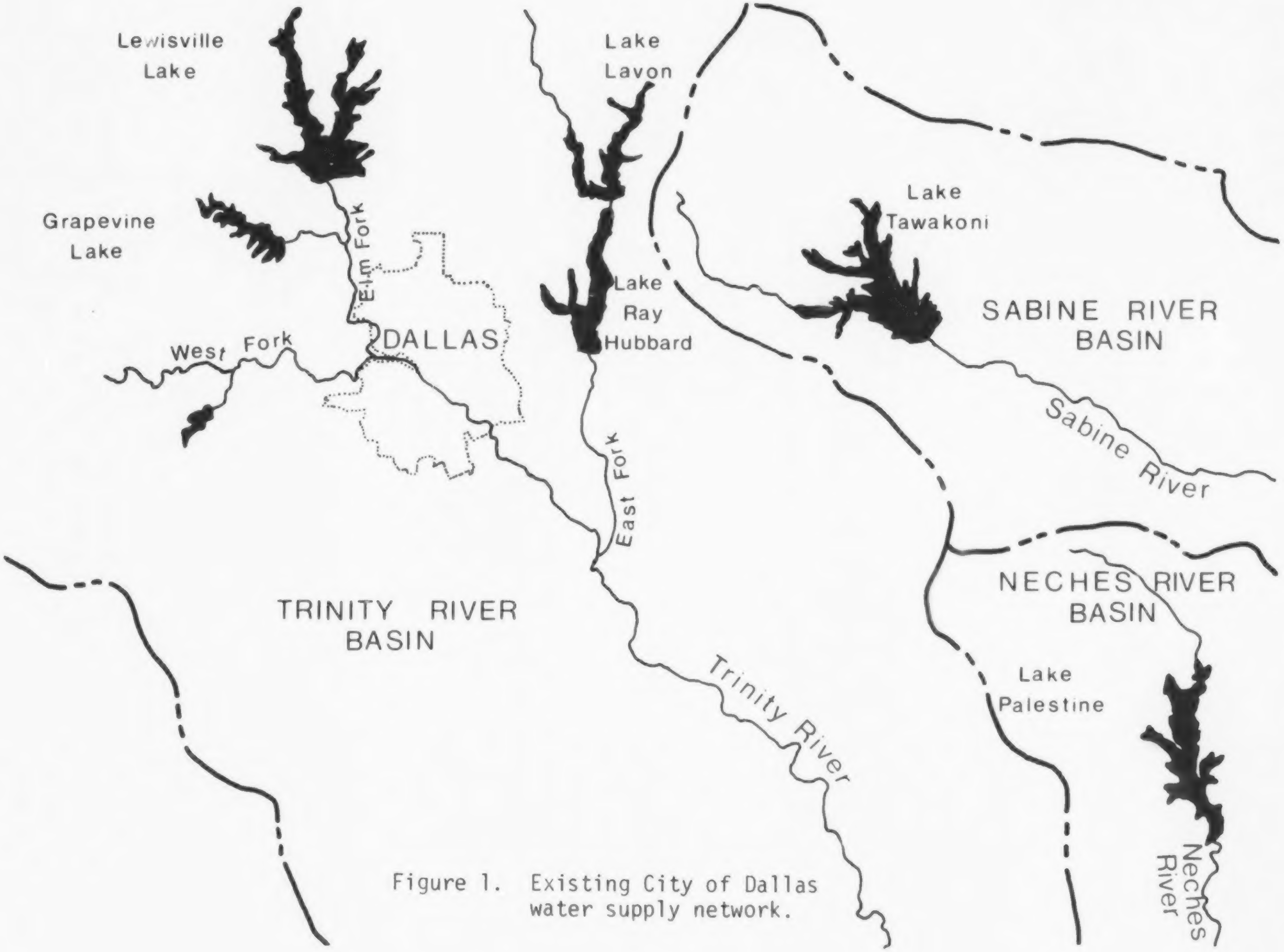

Figure 1. Existing City of Dallas water supply network.

TABLE 1. SUMMARY OF EXISTING WATER SUPPLY FOR THE YEAR 2020

Reservoir and Basin	Estimate Safe Yield M^3/day	MGD
Trinity River Basin		
Lewisville (Garza-Little Elm)	329,000	86.8
Grapevine	38,000	10.0
Ray Hubbard	210,000	55.4
Lavon	38,000	10.0
Return flows	156,000	41.3
Sabine River Basin		
Tawakoni	616,000	162.8
Neches River Basin		
Palestine	386,000	102.0
TOTAL AVAILABLE SUPPLY	1,773,000	468.3

The funds for construction of the laboratory and administration building were provided in part by Federal Grant No. WPC Tex 588, to the amount of $571,093 of which the City provided 52 percent. The Demonstration Plant was constructed under Grant No. 17080 EKG from the Environmental Protection Agency (EPA) for a total cost of $689,015 of which the City of Dallas provided 45 percent.

From start-up until January 1971 the Dallas Water Reclamation Research Center operated on additional funds provided in Grant No. 17080 EKG for the study of various water reclamation unit processes. The initial phase of the project was directed at evaluating different sequences of unit processes to expand and up-grade the City's Central Wastewater Treatment Plant.

At the conclusion of these studies additional unit processes were investigated by utilizing a number of different wastewaters as influents to the unit processes at the Demonstration Plant. For the most part the investigations were short term (2 to 4 weeks), and these data have been presented in the Final Report for the project (2).

RESEARCH PRESENTED IN THIS REPORT

The present project, Grant No. S-801026, was started in June 1972 and research was concluded during February 1974. During this project metals removal and virus removal in various advanced wastewater treatment techniques were evaluated. Each unit process was appraised for the removal of over twenty separate metals as well as the more routine water quality parameters related to process control and overall water quality. During the grant period, research to ascertain the ability of various treatment sequences to remove viruses from an activated sludge effluent was carried out at the research center. A series of four virus seedings were undertaken to study virus removal through the chemical treatment sequence at the pilot plant. The virus studies were jointly carried out between the staff of the research center and Dr. Robert Safferman and staff of EPA.

SECTION 2

CONCLUSIONS

Metals that showed removals by the biological process of 45 percent or better were: Al, Ba, Be, Cd, Cr, Cu, Fe, Mo, Pb, Se, and Zn. Metals that showed poor removals (10 percent or less) were:Ag, As, B, Ca, Na, Si, and Sr. Intermediate removals were demonstrated by Co, Hg, K, Mg, Mn, Ni, and V.

The biological process performed poorly in removing at least two elements of environmental concern: Arsenic and boron. Hence, it is well to consider other means of control of these substances, means which will preclude their contamination of the environment. The importance of monitoring biological processes is also made obvious.

Removal of a number of metals in the biological treatment process tested here was strongly concentration dependent, showing increased removal with increasing influent metal concentration.

High-pH lime coagulation and recarbonation is more effective in removing metals from biologically treated wastewater flows than alum coagulation.

Removals of 50 percent or better were demonstrated for Cr, Fe, Se, Mg, Mn, Zn, Hg, As, Al, Ni, and Pb by biological treatment plus high-pH lime coagulation without recarbonation; for Cr, Fe, Zn, Cu, Se, Mo, Mn, Cd, Pb, Hg, and Ba by biological treatment plus alum coagulation; and for Cr, Se, As, Mn, Cd, Al, Fe, Hg, Pb, Cu, and Mo by biological treatment plus high-pH lime coagulation with recarbonation.

Removals of 20 percent or less were shown for Sr, Si, Ag, B, Na, Co, and Cu by biological treatment plus high-pH lime coagulation without recarbonation; for Co, V, K, Na, Mg, Al, Si, B, Ag, and Ca by biological treatment plus alum coagulation; and for Sr, Na, B, Co, Ca, and Zn by biological treatment plus high-pH lime coagulation with recarbonation.

Chemical-physical processes applied to biologically treated effluents appeared to perform about as well as the literature reports for them in water treatment applications. Alum coagulation removal of virus was a function of Al/P dose used. At low Al/P doses poor virus removal occurs even if good suspended solids removal takes place.

High-pH lime treatment of secondary effluents achieves very high degrees of virus removals. However, after recarbonation, recontamination can occur as there is no residual viricide present.

Biological treatment followed by high-pH lime treatment plus recarbonation appeared to be the most effective of all treatments examined for removing metals. It was also the most effective for removing arsenic, but boron was still relatively untouched. The suggestion is that high-pH lime treatment plus recarbonation is one of the more effective assemblages of unit processes for consideration in reuse applications, but that boron requires consideration on a case-by-case basis.

The use of high-pH lime treatment also provided for excellent disinfection, not only for vegetative forms of bacteria, but also for polioviruses. In reuse applications high-pH lime treament is highly warranted.

Removal of animal virus and coliphage was virtually identical in the treatment processes tested.

Carbon adsorption should not be applied to lime-coagulated water which has not been recarbonated or had its pH reduced to 8.0 because the carbon granules will cement together.

SECTION 3

RECOMMENDATIONS

Additional work appears warranted on the effect of concentration on metals-removal performance of biological processes. Removal of Cd, Co, Mo, and Zn in this study appeared to be strongly related to their concentrations.

In general, the biological process was not efficient for metals removal. It is suggested that the effluents from the biological process be periodically monitored for metals as well as BOD_5 and suspended solids. If the biological process cannot do well in removing a particular undesirable product, other means of control would be indicated.

Additional studies of the feasibility of the use of coliphage as an indicator or tracer of the removal of animal virus in wastewater treatment should be conducted.

SECTION 4

DESCRIPTION OF RESEARCH FACILITIES

CITY OF DALLAS COLLECTION SYSTEM

The sanitary sewer collection system serving the City of Dallas consists of 5074 kilometers (3,137 mi) of gravity mains. The lengths of mains of different diameters are summarized in Table 2. The best available estimates indicate that the total length of laterals is between one and two times the length of the gravity mains, indicating a total collection system length between 10,000 and 15,000 kilometers (6215 and 9323 mi). The City has no combined sewers.

In addition to the normal domestic wastes discharged to the collection system, the City has significant contributions from industrial and commercial establishments. During fiscal year 1973 the industrial discharges represented 12.1 percent of the total flow received at the Central Plant. Total flow received during this period was 17.9×10^7 m^3/yr (47.3×10^9 gal per year). The 221 significant industries monitored by the Water Utilities Department discharged a total of 5.23×10^7 kg of BOD_5 (1.15×10^8 lbs) and 5.34×10^7 kg (1.17×10^7 lbs) of total suspended solids (TSS) to the collection system during FY 1973.

The activities of commercial establishments including restaurants wholesale food preparation facilities, and service facilities (principally car washes), have substantial impact on wastewater characteristics. Generalized information relating to the industrial and commercial discharges are summarized in Table 3. The predominant effect of commercial activities is to increase the organic and solids loadings; however, certain of the services activities (car washing) can have appreciable impact on metals concentrations.

The City of Dallas' Central Wastewater Treatment Plant consists of three major sections; the Dallas Sewage Treatment Plant (STP), the White Rock STP, and the Tertiary Treatment Complex. Each of these components is described in detail in subsequent paragraphs. Both the Dallas and White Rock STP's are older trickling filter facilities, and each plant serves a well defined and separate portion of the City's collection system. The plants operate in parallel and their effluents are discharged to the Tertiary Complex for additional treatment prior to discharge to the Trinity River. The influent pumps for the Demonstration Plant were located at the White Rock STP because it is the closest source of wastewater.

TABLE 2. SIZES AND LENGTHS OF GRAVITY MAINS IN THE SANITARY SEWER COLLECTION SYSTEM.

PIPE DIAMETER		LENGTH	
(cm)	(in)	(km)	(mi)
10.16	4	2.513	1.562
15.24	6	1814.508	1127.724
20.32	8	1934.113	1202.059
25.40	10	450.758	280.148
30.48	12	244.624	152.035
35.56	14	1.759	0.472
38.10	15	176.397	109.658
40.64	16	0.290	0.180
45.72	18	123.037	76.468
53.34	21	59.057	36.704
60.69	24	47.435	29.481
68.58	27	21.334	13.259
76.20	30	40.954	25.453
83.82	33	8.367	5.200
91.44	36	22.632	14.066
99.06	39	7.435	4.621
106.68	42	12.790	7.949
114.30	45	7.416	4.609
121.92	48	16.939	10.528
129.54	51	0.454	0.282
137.16	54	10.095	6.274
152.40	60	26.182	16.272
160.02	63	0.732	0.455
167.64	66	3.560	2.236
182.88	72	8.333	5.179
198.12	78	1.936	1.203
205.74	81	0.714	0.444
213.36	84	1.263	0.785
228.60	90	2.248	1.397
Total length of mains	=	5,047.005	3,136.734

TABLE 3. SUMMARY OF INDUSTRIAL AND COMMERCIAL DISCHARGES TO THE COLLECTION SYSTEM.

Type of Business	Number of Establishments	-------- Flow -------		BOD_5 (mg/l)	TSS (mg/l)	Grease (mg/l)
		(cu.m./mo.)	(gal./mo.)			
Industrial	221	1.824×10^6	4.82×10^8	773	626	----
Commercial						
Restaurants	1700	--------	--------	1158	1059	320
Wholesale Food Preparation	200	--------	--------	903	678	183
Service Facilities	300	--------	--------	268	1079	203
Total Commercial	2200	3.96×10^5	1.05×10^8	---	---	---

The concentrations of certain metals in the influents of the Dallas and White Rock plants are given in Table 4. The column headed "combined" is a calculated, flow-weighted concentration for all wastewaters arriving at the Central Plant which comprises both the Dallas and White Rock plants. Typical characteristics of raw wastewater entering the White Rock STP are presented in Table 5. This wastewater appears to be representative of domestic wastewaters. Most of the industrial waste discharges enter the Dallas STP, and for this reason the wastewater entering the White Rock plant is more suitable for wastewater reuse studies.

TREATMENT FACILITIES

The Demonstration Plant of the Dallas Water Reclamation Research Center is colocated with the White Rock Sewage Treatment Plant (STP) at the City of Dallas' Central Wastewater Treatment Facility. The Central Plant complex is situated on the south bank of the Trinity River approximately five kilometers (3 miles) south of the City's central business district. The Central Plant actually consists of three treatment facilities described below, two of which are trickling filter plants. The third facility is completely-mixed activated sludge followed by tertiary mixed-media filtration.

Dallas Sewage Treatment Plant

The Dallas STP is the oldest wastewater treatment facility operated by the City of Dallas. This single-stage, standard-rate, trickling filter facility consists of four bar screens and grit channels, twenty-four Imhoff tanks which are operated as primary clarifiers, two rectangular primary clarifiers, sixteen standard-rate trickling filters which are 53 meters (174 feet) in diameter and three final clarifiers.

White Rock Sewage Treatment Plant

The White Rock STP is a two-stage, high-rate trickling filter facility without intermediate clarification. The plant consists of two bar screens and grit channels, six rectangular primary clarifiers, four first-stage, high-rate trickling filters, eight second-stage, high-rate trickling filters, and four rectangular final clarifiers. All trickling filters are 53 meters (174 feet) in diameter, and contain a maximum of 2.29 meters (7.5 feet) of media.

Tertiary Treatment Complex

Under normal flow conditions the effluents from both the Dallas and White Rock facilities are discharged to the tertiary treatment complex prior to discharge into the Trinity River. The tertiary complex consists of twelve completely-mixed, activated sludge aeration basins and twelve final clarifiers, followed by fourteen mixed-media gravity filters.

TABLE 4. INFLUENT METALS CONCENTRATIONS* FOR FISCAL YEAR 1973

Metal	Concentration (mg/l)		
	Dallas STP	White Rock STP	Combined
Arsenic	-	-	-
Barium	-	-	-
Boron	-	-	-
Cadmium	0.045	0.0148	0.0224
Chromium	0.347	0.158	0.205
Copper	0.184	0.159	0.165
Lead	0.319	0.176	0.212
Manganese	-	-	-
Mercury	0.00208	0.00103	0.001294
Nickel	0.193	0.118	0.137
Selenium	-	-	-
Silver	-	-	-
Zinc	0.675	0.191	0.312

* Arithmetic means for the fiscal year.

TABLE 5. CHARACTERISTICS OF RAW WASTEWATER AT THE WHITE ROCK STP FOR THE PERIOD OF JUNE 1, 1972 THROUGH FEBRUARY 27, 1974

Flow = 316,048 m^3/day (83.5 MGD)

Grit = 0.0274 l/m^3 (3.66 cu.ft./MG.)

Total Solids = 912 mg/l

Settleable Solids = 8.9 ml/l

TSS = 241 mg/l

BOD_5 = 200 mg/l

NH_3-N = 17.4 mg/l

Org. N = 12.7 mg/l

NO_2 & NO_3-N = 0.5 mg/l

pH = 7.3

Demonstration Plant

All influents to the Demonstration Plant are pumped from the White Rock STP and all effluents and sludges from the pilot plant are returned to the headworks of the White Rock plant. As indicated in Figure 2, there are a total of five possible influents which can be supplied at a maximum flow of 47.3 liter/sec (750 gpm), with the exception of the raw sewage pump that is rated at 18.9 liters/sec(300 gpm). The discharges from all pumps are routed to a valve station at the White Rock plant, from which the flow is directed to the pilot plant through one of three main influent lines. Each influent line services one of the major treatment modules (biological, chemical, or physical) at the Demonstration Plant.

As indicated in Figure 3, which is a piping diagram of the major components of the Demonstration Plant, the facility is relatively complex and very flexible. The following unit processes are present at the pilot plant. They are discussed in detail in the following sections of this report, and many are identified in Figure 4 (aerial photograph of the Demonstration Plant).

1. No. 1 completely-mixed activated sludge system
2. No. 2 completely-mixed activated sludge system
3. Upflow clarifier
4. Gravity-flow, mixed-media filter
5. Gravity-flow, dual-media filter
6. Gravity-flow activated carbon contactors (2 each)
7. Chlorine contact basins (2 each)
8. Ozone generator and contacting system
9. Reverse osmosis demineralization unit
10. Ultraviolet light disinfection unit
11. Chemical storage and feeding equipment

No. 1 Activated Sludge System--

The No. 1 activated sludge system consists of the No. 1 aeration basin and the No. 1 final clarifier, and return sludge and effluent pumps. The return sludge pump has a practical operating range of 6.3 to 47.3 liters/sec. (100 to 750 gpm), while the effluent pump has an operational range of 3.2 to 20.5 liters/sec. (50 to 325 gpm).

No. 1 Aeration Basin--

The No. 1 aeration basin is a circular mild-steel tank erected above ground; technical data for this unit are summarized in Table 6. Figure 5

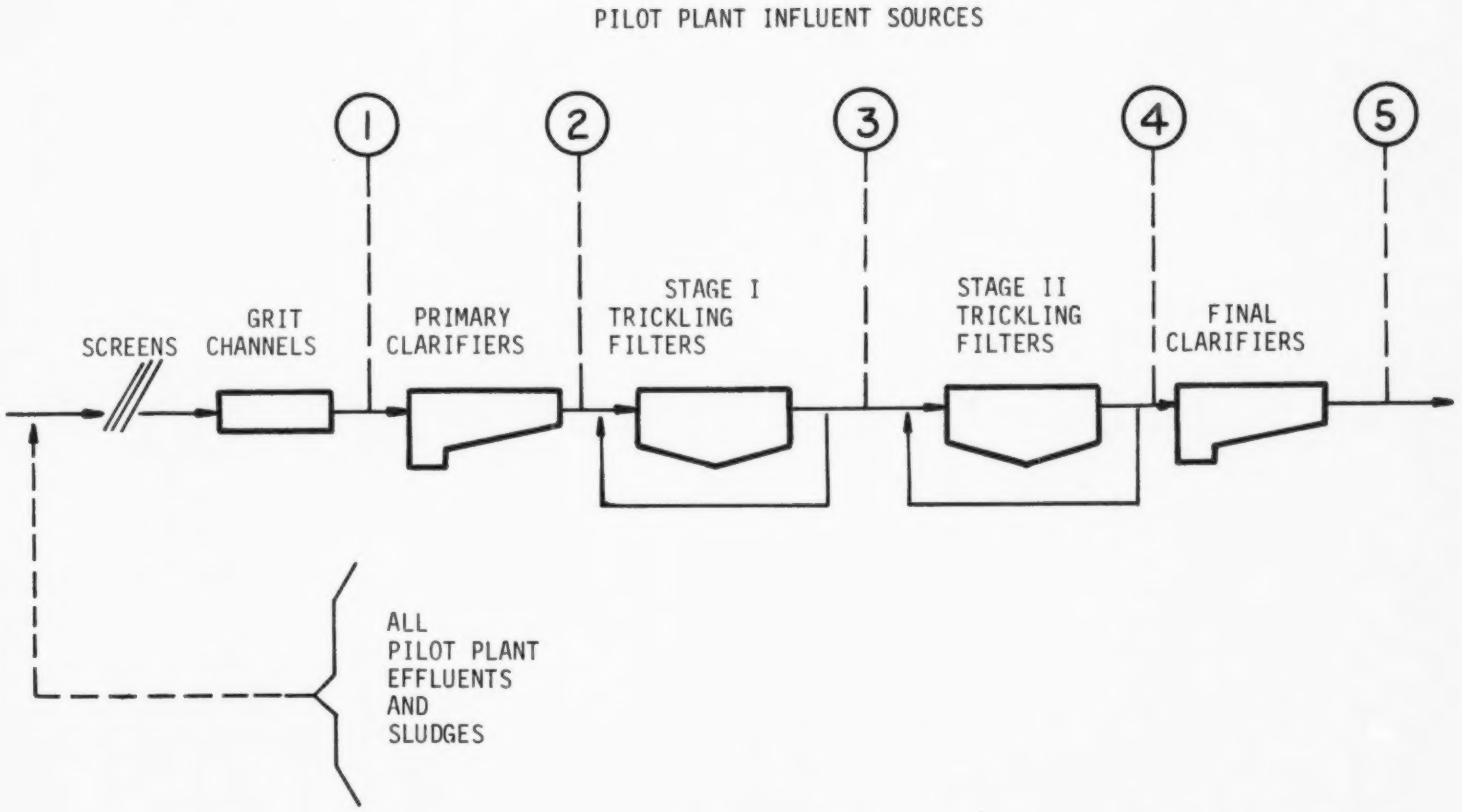
PILOT PLANT INFLUENT SOURCES
1
2
3
4
5
SCREENS
GRIT CHANNELS
PRIMARY CLARIFIERS
STAGE I TRICKLING FILTERS
STAGE II TRICKLING FILTERS
FINAL CLARIFIERS
ALL PILOT PLANT EFFLUENTS AND SLUDGES

Figure 2. Possible sources of influents for the Pilot Plant at the White Rock Sewage Treatment Plant

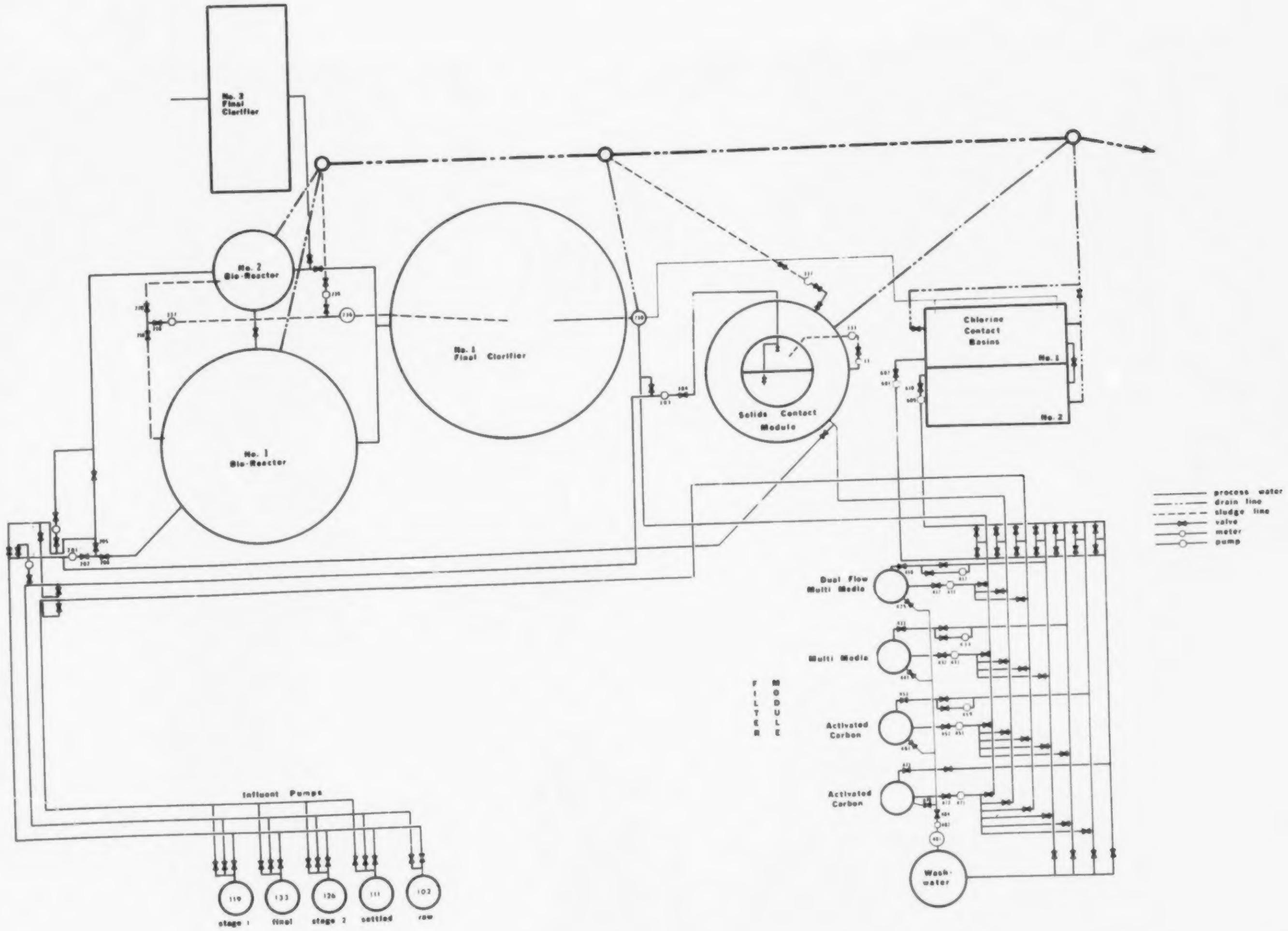

Figure 3. Dallas Water Reclamation Research Center - Demo Plant

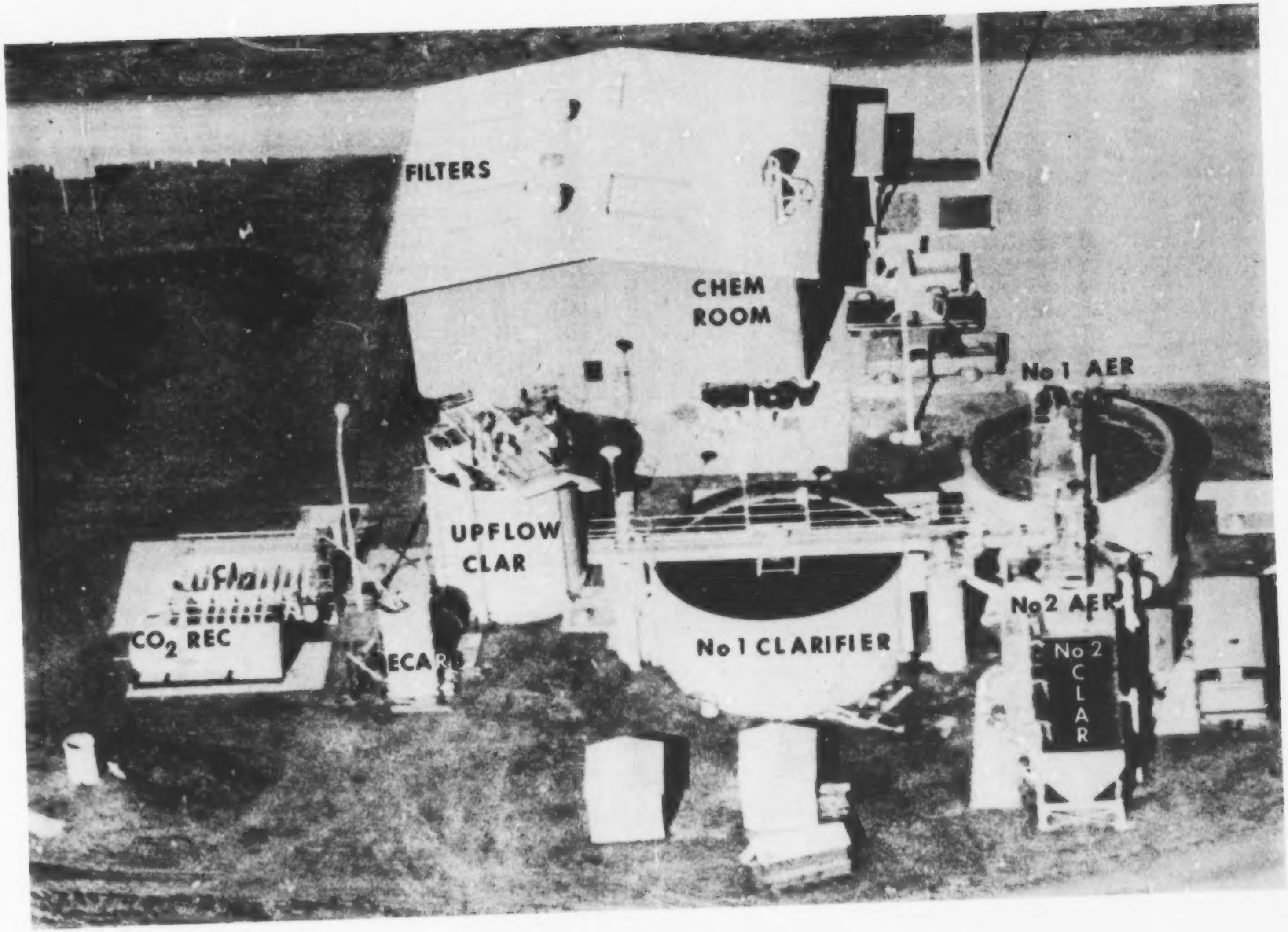

Figure 4. Aerial photograph of the Demonstration Plant.

TABLE 6. TECHNICAL DATA FOR THE NO. 1 AERATION BASIN.

Diameter	=	7.62 m (25.0 ft.)
Depth	=	3.66 m (12.0 ft.)
Volume	=	170,343 liters (45,000 gal.)
	=	560.2 m^3 (6,030 $ft.^3$)
Theoretical Residence Time at 6.3 liters/sec (100 gpm)	=	7.5 hours
Total Nameplate Power Input	=	29.8 kw (40 HP)
Maximum Power Level	=	0.053 kw/m^3
	=	(0.89 HP per 1000 gal.)
	=	(6.64 HP per 1000 $ft.^3$)
Air Flow	=	118 or 236 liters/sec
	=	(250 or 500 scfm)

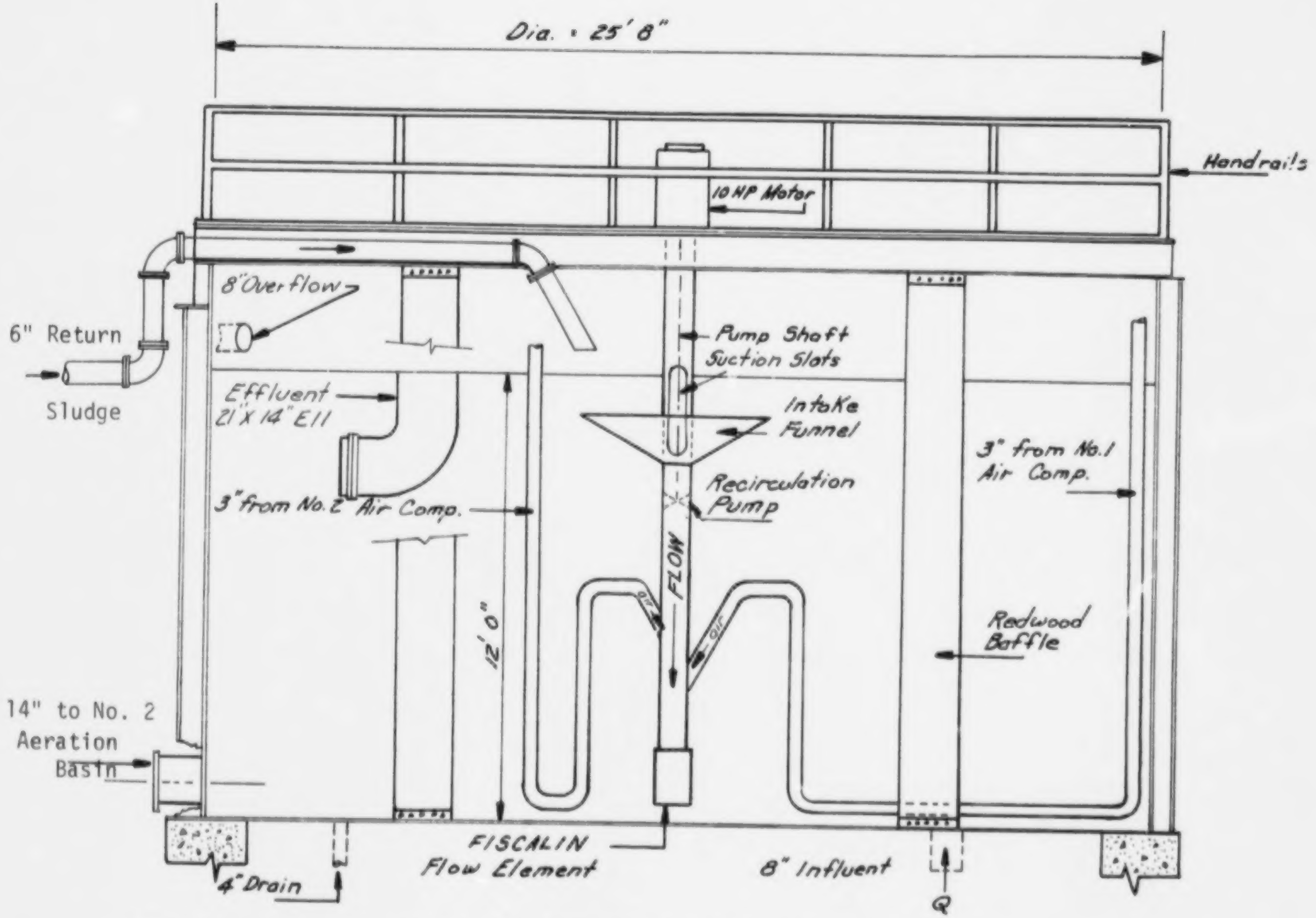

Figure 5. No. 1 Aeration Basin with Aquarius Oxygen Transfer Equipment.

indicates the major structural features of interest.

Several different types of mixing and oxygen transfer equipment have been evaluated in this basin. Aquarius, Inc. supplied the Fiscalin system, which was operated throughout most of this grant. As shown in Figure 5, the Fiscalin system consisted mainly of a center draft tube, a submersible pump within the draft tube, and the Fiscalin flow element at the bottom of the draft tube. The submerged pump pumped the mixed liquor down the draft tube through the Fiscalin flow element, which would divert the flow into the rest of the tank. Oxygen transfer was accomplished by injecting air into the draft tube at four points below the pump. The Fiscalin flow element created a high shear area which resulted in the formation of very small air bubbles.

No. 1 Final Clarifier--

The No. 1 final clarifier is a circular, mild-steel basin erected above ground. As initially provided by Rex Chainbelt, the unit had peripheral feed and square effluent weirs in the center of the tank. This unit was not originally equipped with a surface skimmer, and the center effluent weir configuration made addition of a skimmer, quite complex. Therefore, the basin was modified by removing the center effluent weirs and bolting a new peripheral effluent weir to the inside of the existing influent baffle skirt. A skimmer and scum collector were then fitted to the basin. These modifications are shown in Figure 6 .

Sludge is removed by the head differential between the water surface in the clarifier and the return sludge pump well, via a header. Technical data for this clarifier are presented in Table 7.

No. 2 Activated Sludge System--

The No. 2 activated sludge system consists of the 28.4 m^3 (7,500 gal) completely-mixed aeration basin, and a three-hopper Smith and Lovelace final clarifier with a sidewater depth of 3.66 m (12.0 ft.). Mixing and oxygen transfer is effected by diffusers, and the maximum air flow is 53.8 liters/sec (144 scfm).

Upflow Clarifier--

An Infilco Densator, shown in Figure 7, is the chemical treatment unit used at the Demonstration Plant. The unit consists of the main tank, 5.5 m (18 ft.) in diameter and 5.48 m (18 ft.) deep, and an inner cylinder that serves as the rapid mixing and flocculation zones. Influent enters the top of the inner cylinder, and the annulus between the inner cylinder and the main tank serves as the upflow clarification compartment.

Energy input for mixing and flocculation is supplied via independent turbine-type mixers, each of which is equipped with a U.S. Electric Varidrive that has a 10 to 1 turndown capability.

A 2.54 cm x 10.16 cm (1 in. x 4 in.) steel fluidizer bar is used to prevent the sludge from over-compacting. Table 8 summarizes the more significant technical information on the upflow clarifier.

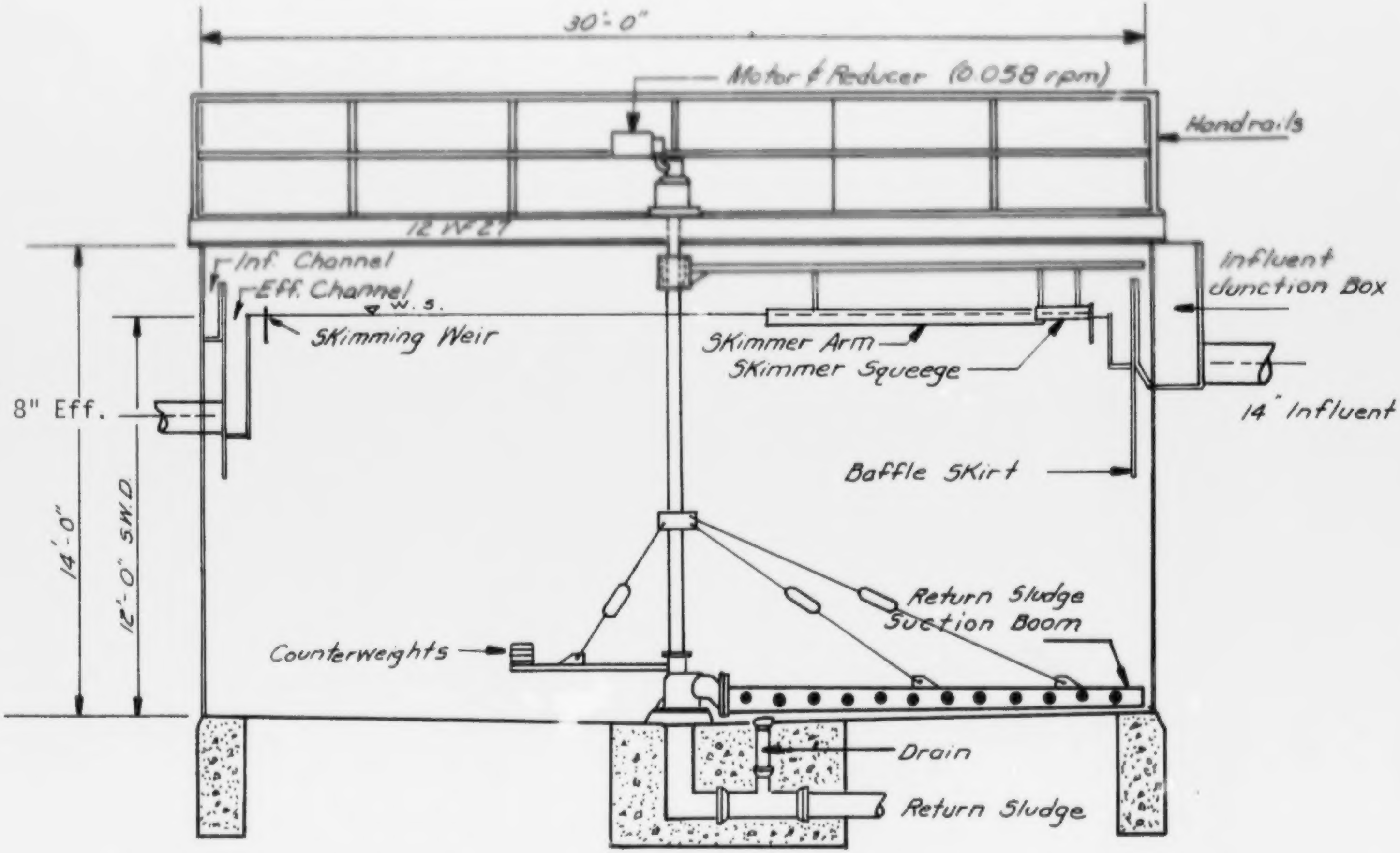

Figure 6. Section of the No. 1 Final Clarifier after Modifications.

TABLE 7. TECHNICAL DATA FOR THE NO. 1 FINAL CLARIFIER.

Diameter	=	9.14 m (30.0 ft.)
Depteh	=	3.66 m (12.0 ft.)
Volume	=	240,373 liters (63,500 gal.)
	=	240.4 m^3 (8,480 ft.^{3})
Surface	=	65.68 m^2 (707 ft.^{2})
Weir Length	=	27.13 m (89 ft.)
Surface Overflow Rate at 6.3 liters/sec (100 gpm)	=	8.50 m^3/m^2/day (203.7 gpd/ft^2)
Weir Loading at 6.3 liters/sec (100 gpm)		20.09 m^3/m/day 1618 gpd/ft.)

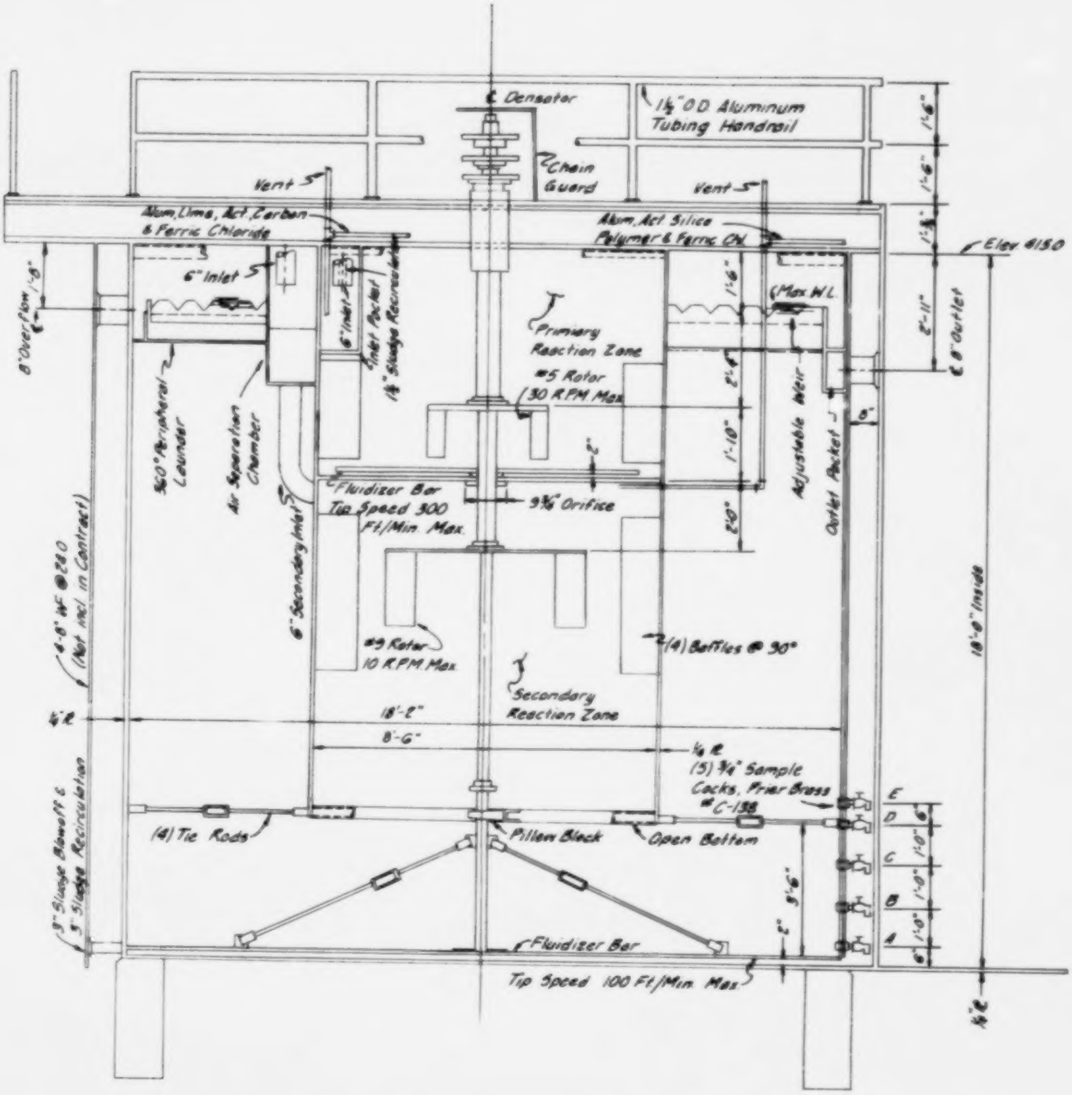

Figure 7. Elevation of the upflow clarifier.

TABLE 8. TECHNICAL DATA FOR THE UPFLOW CLARIFIER.

Rapid Mixing Zone

Diameter = 2.59 meter (8.5 ft.)
Depth = 0.64 meters (2.1 ft.)
Surface Area = 5.26 sq.m. (56.6 sq.ft.)
Volume = 3.35 cu.m. (886 gal.)
Residence Time at 6.31 liters/sec (100 gpm) = 8.86 min.
Mixing = 3 to 30 rpm

Flocculation Zone

Diameter = 2.59 meters (8.5 ft.)
Depth = 3.29 meters (10.8 ft.)
Volume = 17.3 cu.m. (4,570 gal.)
Residence time at 6.31 liters/sec (100 gpm) = 45.7 min.
Mixing = 1 to 10 rpm

Upflow Clarification Zone

Outside diameter = 5.54 meters (18.167 ft.)
Inside diameter = 2.59 meters)8.5 ft.)
Volume = 96.8 cu.m. (25,580 gal.)
Surface Area = 18.71 sq.m. (201.4 sq.ft.)
Overflow rate at 6.31 liters/sec (100 gpm) = 29.9 m^3/m^2/day (717 gpd/sq.ft.)
Weir loading at 6.31 liters/sec = 33.5 m^3/m/day (2,700 gpd/ft.)
Residence time at 6.31 liters/sec = 255.8 min.

Total theoretical residence time at 6.31 liters/sec (100 gpm) = 5.17 hours

Chemical Storage and Feed Equipment--

Facilities are present at the Demonstration Plant to store and feed the following chemicals:

1. Hydrated lime
2. Hydrated aluminum sulfate
3. Ferric chloride
4. Dry polyelectrolytes
5. Liquid polyelectrolytes
6. Activated silica
7. Powdered activated carbon
8. Chlorine

All coagulants and coagulant aids, with the exception of lime, can be fed to either aeration basin or final clarifier, to the upflow clarifier, or in front of the filters or carbon contactors for use as filtration aids. The lime slurry can be pumped to either of the activated sludge systems or the upflow clarifier.

No. 1 Mixed-Media Filter--

The No. 1 filter is shown in Figure 8 as it was initially installed at the Demonstration Plant. At that time the filtering media consisted of 0.91 meters (3.0 feet) of sand overlayed with 0.30 meters (12 inches) of anthracite. The influent flow was split equally between the top and bottom of the filter bed, and the effluent was withdrawn through a mid-bed collector located 15 cm (6 inches) below the sand-anthracite interface. The filter performance can be characterized as having been generally good; however, structural deficiencies with the mid-bed collector resulted in frequent maintenance and the unit was converted to a conventional gravity flow filter.

When the filter was rebuilt in December 1971 media supplied by Neptune Microfloc was utilized and the media specifications are summarized in Table 9. The filter has a nominal diameter of 1.22 meters (4.0 feet) and a surface area of 1.17 sq.m. (12.57 sq.ft.). At a flow of 2.37 liter/sec. (37.5 gpm) the filtration rate is 2.03 liter/sec/m^2 (3 gpm/sq.ft.). The filter was normally backwashed at a flow of 12.2 liters/sec/m^2 (18 gpm/ft^2) for ten minutes. The surface wash was started two minutes prior to starting the main backwash flow, and stopped two minutes before the backwash was terminated. The surface wash flow was not measured, but a good visual estimate is approximately 0.9 liters/second (15 gpm).

During the course of the different research projects conducted at the Demonstration Plant the bed expansion on the No. 1 filter was measured.

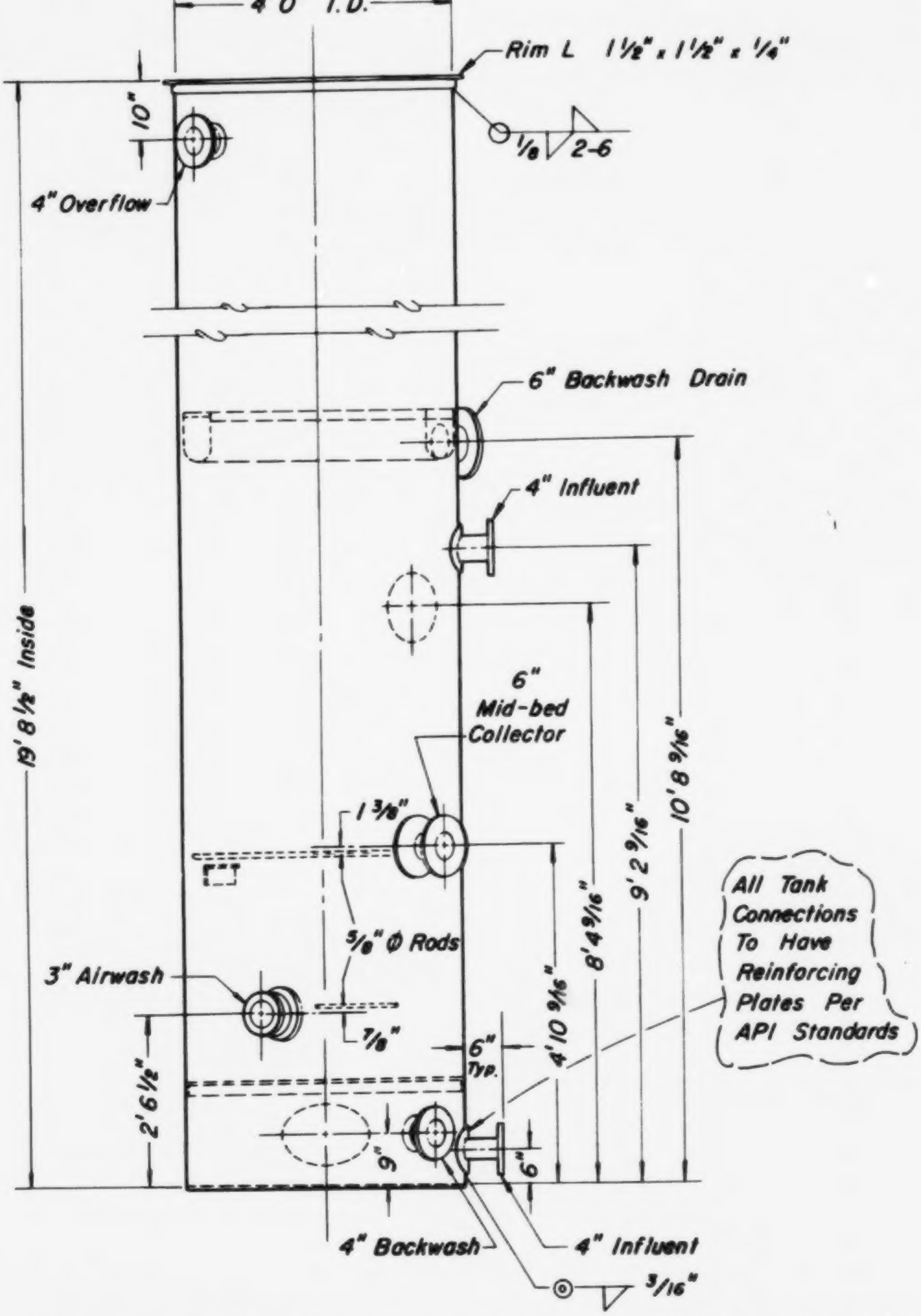

Figure 8. Typical elevation of the No. 1 and No. 2 gravity filters.

TABLE 9. MEDIA SPECIFICATIONS FOR THE NO. 1 MIXED-MEDIA FILTER

Material	Size	Depth	Effective Size	Uniformity Coefficient
Gravel	1.905 to 1.27 cm	7.62 cm (3 in.)		
	1.27 to 0.635 cm (1/2 to 1/4 in.)	7.62 cm (3 in.)		
	<0.635 cm (<1/4 in.)	5.08 cm (2 in.)		
Garnet				
Coarse, MS-11		7.62 cm (3 in.)	0.87 mm	1.17
Fine, MS-7		11.43 cm (4.5 in.)	0.27 mm	1.22
Sand, MS-18		24.13 cm (9.5 in.)	0.41 mm	1.32
Anthracite, MS-19		55.88 cm (22 in.)	1.05 mm	1.35
Total Depth of Filter Media = 99.06 cm (39 inches)				

These data were obtained at different backwash flows and water temperatures and are presented in Figure 9. The effect of backwash water temperature on bed expansion is clear, and can be directly attributed to decreased viscosity of the backwash water at the higher temperatures.

It should be noted that during the summer, wastewater temperatures approaching 30°C are not uncommon in the South and Southwest. The data presented in Figure 9 suggest that backwash water pumps and distribution systems, in regions with high water temperatures, should be designed for flows that are significantly higher than conventional design flows of 10 to 13.5 liters/sec/m^2 (15 to 20 gpm/ft^2).

No. 2 Dual-Media Filter--

Structurally, the No. 2 filter is almost identical to the No. 1 filter, and this unit is also operated in the conventional gravity-flow mode. Media consist of 30.48 cm (12 inches) of sand with a 60.96 cm (24 inches) anthracite cap. The filter sand has an effective size of 0.57 mm and a uniformity coefficient of 1.6, and the anthracite an effective size of 0.96 mm and a uniformity coefficient of 1.5. Air scour is normally used prior to backwash at a rate of 20.2 liters per sec. per sq.m. (4 scfm per sq.ft.).

Activated Carbon Contactors--

Both the No. 3 and No. 4 columns at the Demonstration Plant serve as granular activated carbon contactors, and construction details are shown in Figure 10 Both units are 1.22 meters (4.0 feet) in diameter and use a 3.05 meter (10.0 foot) charge of carbon, or 2000 kg (4400 lbs.) at a bulk density of 0.56 kg per liter (35 lbs. per cu.ft.). The carbon contactors use the same air scrubbing system for backwashing as the No. 2 filter. Calgon Filtrasorb 300, 8x30 mesh activated carbon was used throughout the study.

Chlorine Contact Basins--

The Demonstration Plant has two chlorine contact basins which may be operated in parallel or in series. Each basin is 5.49 meters (18.0 feet) long, 2.26 meters (7.41 feet) wide, and 0.48 meters (1.58 feet) deep. Each basin has a volume of 5.95 cu.m. (1573 gal.), which results in a theoretical residence time of 15.7 minutes at a flow of 6.31 liters per sec. (100 gpm). Eleven fiberglass baffles were installed in each basin, such that plug flow would be closely approximated. Dye studies have been used to quantify the hydraulic charateristics of the end-around baffling system, and observed residence time distribution functions closely approximate theoretical values. The chlorination equipment is capable of a maximum feed of 22.7 kg (50 lbs.) of chlorine per day.

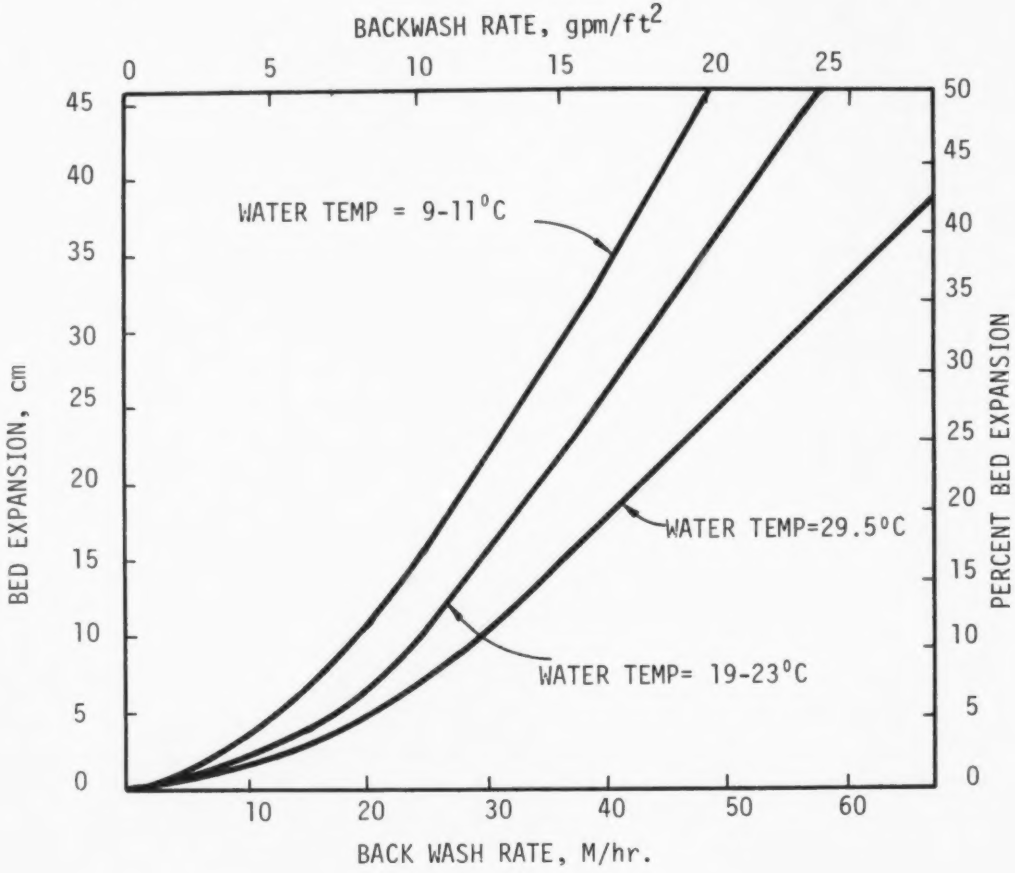

Figure 9. Media expansion as a function of temperature and backwash rate for the No. 1 multimedia filter.

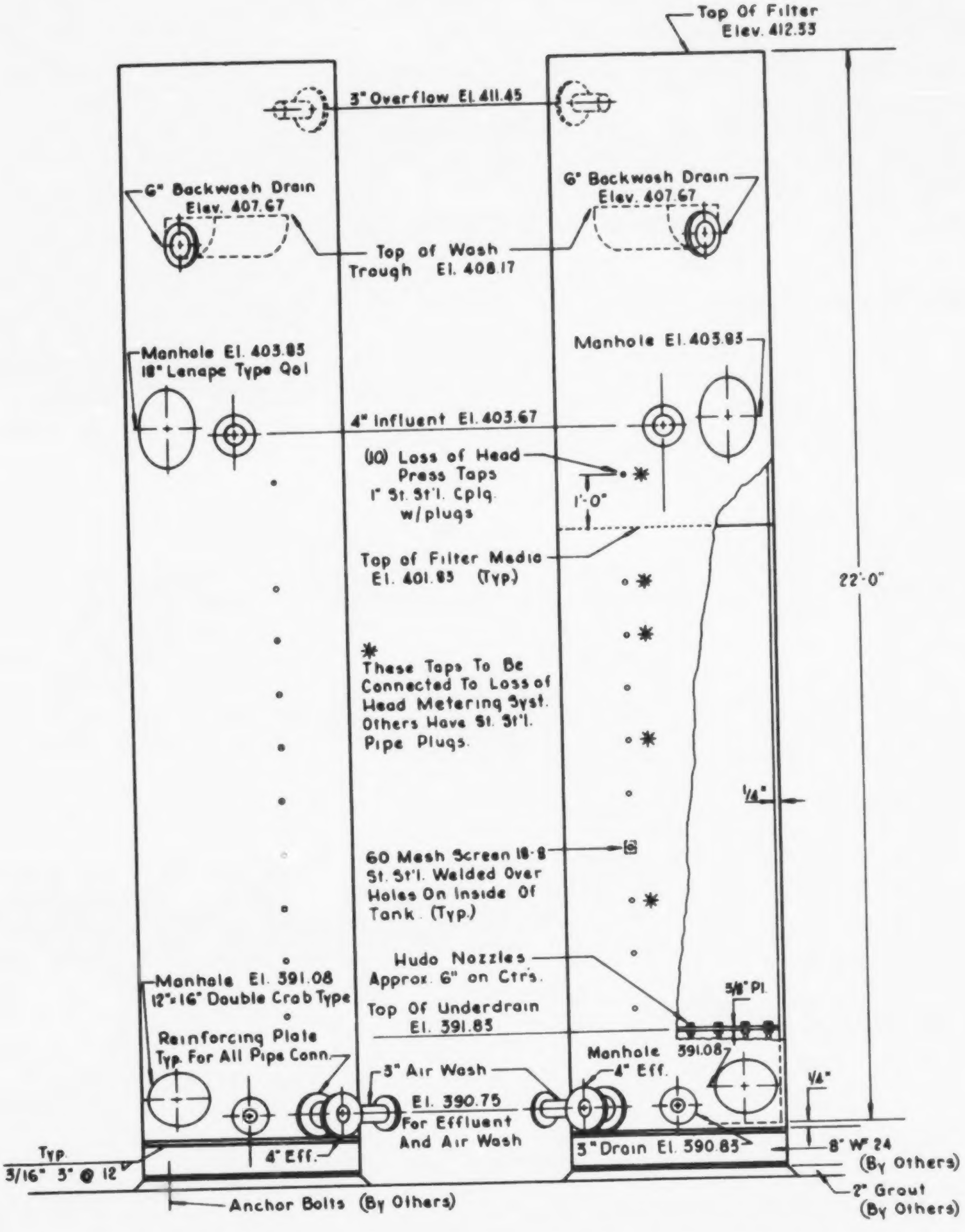

Figure 10. Elevation of downflow granular activated carbon contactors.

SECTION 5

SAMPLING AND ANALYTICAL PROCEDURES

SAMPLING PROCEDURES

The sampling procedures described below were utilized for the duration of this research effort. Samples for routine wet chemistry and metals analyses were collected by the operators on duty at the Demonstration Plant, and samples for microbiology were collected by microbiology laboratory technicians.

Routine Chemistry Samples

Samples for routine wet chemistry analyses were collected by the plant operators seven days a week at 1:00 am, 5:00am, 9:00am, 1:00pm, 5:00pm, and 9:00pm. Wide-mouth, half-pint plastic bottles were used for sample collection. These sample bottles were placed in a refrigerator until transported to the laboratory, at which time they were composited by the staff chemists. Since the Demonstration Plant was operated at hydraulic steady-state, equal volumes (400 ml) of each of the six grab samples were used for the 24-hour composite sample.

Metals Samples

Samples for metals determinations were collected by the plant operators at the same time samples for routine analyses were collected. Four-hundred milliliter fractions were composited in one-gallon amber bottles to which redistilled nitric acid (10 ml per liter) had been previously added for sample preservation.

Microbiological Samples

Either the staff microbiologist or the microbiology laboratory technicians collected all samples for microbiological evaluation. The samples were collected in 125 ml, wide-mouth glass bottles with glass stoppers that had been previously dry sterilized at 177°C for one hour.

Sampling Frequency

Most of the more conventional water quality parameters that had process control significance were evaluated daily on 24-hour composite samples. Those parameters necessary for general background information, such as chlorides and sulfates, were evaluated on weekly composite samples. Samples were collected for metals analyses every other day.

ANALYTICAL PROCEDURES

The analytical procedure used in this research effort followed the 13th Edition of Standard Methods for the Examination of Water and Wastewater in so far as practicable (3).

Flow

The influent flows to all unit processes, with the exception of the recarbonation basin, were measured by BIF/Brooks magnetic flow meters. This combination of meters and recorders proved to be unreliable, and instrumentation technicians found it impossible to keep the flow meters properly calibrated and maintained. These problems resulted in the installation of several physical flow measuring elements such as orifices, weirs and venturi sections in order that accurate flow measurements could be obtained.

Chemical Oxygen Demand

The following procedures were utilized to determine COD values on the routine samples. The low-level technique was employed for those samples where the COD was expected to be less than 50 mg/l.

High-Level Technique--

The procedure used was as described in Section 220 of Standard Methods.

Low-Level Technique--

The COD of low-level samples was determined by using the procedure given on page 19 of Methods for Chemical Analyses of Water and Wastes 1971 (4). Two modifications were made to the procedure. The amount of mercuric sulfate was reduced from 1.0 to 0.4 grams, and the ferrous ammonium sulfate solution was 0.01 N instead of 0.025N.

Total Organic Carbon

All total organic carbon determinations were made using a Beckman Model 915 Total Carbon Analyzer.

Total Residue

Total solids determinations were made by employing the procedure in Section 224A of Standard Methods.

Nonfiltrable Residue

Total suspended solids determinations were made by employing the procedure in Section 224C of Standard Methods using 2.4 cm diameter glass-fiber filters and Gooch crucibles.

Total Dissolved Solids

Total dissolved solids were computed by subtracting the nonfiltrable residue from the total residue.

Total Phosphorus

The single reagent method given in Methods for Chemical Analyses of Water and Wastes 1971 was used for all total phosphorus determinations. The amount of ammonium persulfate used was increased from 0.4 to 0.5 grams, and the amount of combined reagent was increased from 8 ml to 10 ml.

Ammonia Nitrogen

Ammonia nitrogen determinations were made by using an ion-specific electrode and the Known Addition Method (5). The electrode used was an Orion Model 95-10.

Total Kjeldahl and Organic Nitrogen

Total Kheldahl nitrogen was determined by using an ion-specific electrode and the Known Addition Method after completing the digestion phase of the procedure given in Section 216 of Standard Methods. Organic nitrogen was determined by subtracting the ammonia nitrogen from the total Kheldahl nitrogen.

Nitrite Nitrogen

Nitrite nitrogen determinations were made using the procedure described in Section 134 of Standard Methods.

Nitrate Nitrogen

The phenoldisulfonic acid method, Section 213D of Standard Methods, was used to determine combined nitrite-nitrate nitrogen.

Sulfate

Sulfate was determined by an indirect atomic absorption spectroscopy method by adding a known concentration of barium chloride to form a barium sulfate precipitate. The barium concentration in solution was then determined by atomic absorption, and the sulfate concentration determined by subtraction, as outlined in the Perkin-Elmer Applications Manual.

Chloride

Chloride concentrations were determined by the mercuric nitrate method described in Section 112B of Standard Methods.

Alkalinity

Total and phenolphthalein alkalinity was determined by using the procedures given in Section 102 of Standard Methods using methyl orange and phenolphthalein.

Turbidity

Turbidity was determined by the nephelometric method described in Section 163A of Standard Methods with a Hach Model 2100A Turbidimeter. The standard references were formazin polymer suspensions.

Color

Color determinations were made by plant operators using a Hellige Aqua Tester and platinum-cobalt color disk.

Metals Determinations

Samples for metals analyses were filtered through a glass fiber filter and then concentrated by a factor of ten. Concentration was accomplished by heating (below the boiling point) a 500 ml sample until the volume was reduced to less than 50 ml, and then making up to volume in a 50 ml volumetric flask.

Atomic Absorption--

Atomic absorption spectroscopy was utilized to determine the concentrations of aluminum, barium, cadmium, calcium, cobalt, copper, chromium, iron, lead, magnesium, manganese, silver, strontium, and zinc. A Perkin-Elmer Model 403 was used for these analyses, and standard procedures given in the Perkin-Elmer Operator's Manual (6) and Standard Methods were employed.

Flame Emission--

Sodium and potassium concentrations were determined by flame emission spectrophotometry by operating the PE 403 in that mode, and using methods given in Standard Methods.

Arsenic--

Arsenic concentrations were determined by using the silver diethyldithiocarbamate method presented in Section 104A of Standard Methods.

Boron--

The curcumin method given in Section 107A of Standard Methods was used to determine boron concentrations, with an ion-exchange modification to remove cationic interferences.

Beryllium--

The morin fluorometric method (7) was employed for beryllium determinations.

Mercury--

Mercury concentrations were determined by the flameless atomic absorption method with a Perkin-Elmer Model 290B atomic absorption spectrophotometer.

Molybdenum--

The dithiol method of Brown, et al. (8) was used to determine molybdenum concentrations.

Selenium--

Selenium concentrations were determined by employing the diaminobenzidine method given in Section 150A of Standard Methods.

Silica--

Silica determinations were made by using the heteropoly blue method given in Section 151C of Standard Methods.

Vanadium--

The catalytic oxidation method presented by Brown, et. al. (U.S. Geological Survey) was used to determine vanadium concentrations (8).

VIRUS DETERMINATIONS

When the virus studies were first conceived, it was thought that surplus stocks of vaccine strains of poliovirus could be purchased for use in seeding the various unit processes, The grant which funded the studies provided the assistance of the National Environmental Research Center (NERC) virology program in Cincinnati. NERC was supposed to help by obtaining the viruses, preparing and titering the stocks for seeding, and processing the samples from the experiments, thus performing the key functions. The price quotations NERC received for the attenuated viruses were prohibitive, and NERC had to resort to its own resources for growing the viruses.

Stock

The stock culture used for the virus study were the Poliovirus type I (vaccine strain), f2 Coliphage, and *E. coli* K12 (f+) indicator cells.

Poliovirus Assay

One- to four-liter samples were collected during the experimental runs in gas-sterilized flexible Cubitainers, capped, and placed in ice. The samples were shipped by air in insulated boxes containing ice pre-frozen in watertight quart-size Cubitainers, and arrived in Cincinnati the same night (except for the last shipment -- run No. 4, which did not arrive until noon the following day in spite of all possible efforts to insure prompt handling). The shipments were picked up at the airport and taken to the NERC Cincinnati laboratory by EPA personnel. All samples (except sludge) were Swinny-filtered with 0.45 μ Millipore filter membranes treated with Tween 80 and then inoculated onto BGM (Barron Green Monkey Kidney tissue) cell lines using 1/2 ml in each of 4 bottles for each dilution. For sludge samples, approximately 200 ml of sample was centrifuged and a 15 gram portion of the centrate placed in a beaker. To this residue was added 40 ml of 10 percent buffered beef extract (Oxoid, Lab Lemco Powder, Flow Laboratory, Rockville, Maryland) which was mixed for 30 minutes on a magnetic mixer and then Swinny filtered with a 0.45 μ Millipore membrane. All of the filtrate was then inoculated onto BGM cell lines using 1 ml per bottle (approximately 40 bottles).

Coliphage Media

The coliphage media consisted of three substances: Tryptone broth, tryptone overlay agar, and tryptone plating agar. The tryptone broth consisted of 10 mg/l of Tryptone (Difco 0123), 1.0 g/l of yeast extract (Difco 0127), 1.0 g/l of glucose, 8.0 g/l NaCl, and 0.22 g/l of $CaCl_2$. Tryptone overlay agar was the same as tryptone broth with the addition of 7.0 g/l agar (Difco 0140). Tryptone plating agar was the same as tryptone broth with the addition of 15 g/l of agar. The salt diluent was 8.5 g/l CaCl and 0.22 g/l $CaCl_2$. Media and diluent were sterilized by autoclaving at 15 psi and 121°C for 15 minutes. Glassware was sterilized in a hot air sterilizer at 170°C for two hours.

Coliphage seed

An overnight culture of *E. coli* K12 (f^+) was diluted 1:100 in one liter of tryptone broth. The culture was grown on a shaker at 37°C to an optical density of 0.2-0.3 which was approximately 10^8 cells/ml. The culture was infected with f2 coliphage at a multiplicity of infection (MOI) of 3, and grown for 4-6 hours longer on the shaker. Twenty to thirty milliliters of chloroform were added and it was refrigerated overnight. The following day, the culture was centrifuged at 16,000 G for 20 minutes at 4°C to remove cellular debris. The supernatant yielded a stock suspension with a titer of at least 1 x 10^{11} pfu/ml.

Coliphage Assay

Samples of 10 ml were collected and 1/2 ml chloroform was added immediately. The samples were stored in a refrigerator overnight. The next day, the following procedure was utilized. To sterile aluminum-capped tubes in a 47°C water bath, the following mixture was added: 2.5 ml molten tryptone overlay agar, 2.0 ml of *E. coli* K12 indicator cells diluted in tryptone broth to a concentration of 10^7 cells/ml, and 0.5 ml of sample containing the phage or, if necessary, 0.5 ml of a 10-fold serial dilution. Salt diluent was used to make the sample dilutions. The tube contents were mixed on a vortex mixer. Contents were poured onto a petri plate containing 20 ml of solidified tryptone plating agar. The plate was swirled to evenly distribute the overlay agar and then allowed to solidify. The plates were inverted and incubated 18 hours at 37°C. Plaques were then counted and the titer calculated.

According to the Health Department requirements, all workers were immunized against polio.

SECTION VI

HIGH-pH LIME COAGULATION

GENERAL

During the first phase in the investigation of metals removals, the Demonstration Plant process configuration was as shown in Figure 11. The upflow clarifier (Infilco Densator) was operated as a high-pH lime coagulation process in this portion of the project, and the target effluent pH range was 11.3 to 11.5. Work commenced in June 1972 and terminated in October 1972, but was resumed briefly in November and December of 1973. The month of July 1972 was excluded because of a change in process configuration, hence, the exact dates for investigation of high-pH lime coagulation without recarbonation were: June 1-31, August 1-October 31, 1972 and November 2-December 9, 1973.

During the first three months, i.e., June through August, the sludge age in the activated sludge system averaged slightly less than 5 days, allowing only partial nitrification. However following installation of the Fiscalin aeration equipment and another air compressor in the first week of August, the ability to nitrify was greatly enhanced, and almost complete nitrification was maintained thereafter.

The multimedia filters were operated at an average rate of 6.11 m/hr. (2.5 gpm/ft^2). The No. 1 (Neptune-Microfloc tri-media) and the No. 2 (conventional dual-media) filters were alternated during this project. One filter processed the activated sludge effluent, while the other filtered the effluent from the chemical treatment process. The No. 1 filter provided the higher degree of suspended solids and turbidity removal, although the performance of either filter was sufficient to produce a product water with turbidities less than 2 NTU, when a properly coagulated effluent was filtered. Flow from the filter was then pumped through one of the two carbon columns, which provided a theoretical empty-bed contact time of 37 minutes.

A water quality summary for the high-pH lime coagulation sequence is presented on Table 10. In spite of large reductions in the concentrations of various pollutants, there were net increases in TDS, specific conductance, alkalinity, NO_2 and NO_3-N. As discussed later in this section, increases were also observed in the concentrations of some metals.

One important aspect of the high-pH lime train was that no effort was made to recarbonate or otherwise neutralize the Densator effluent. The

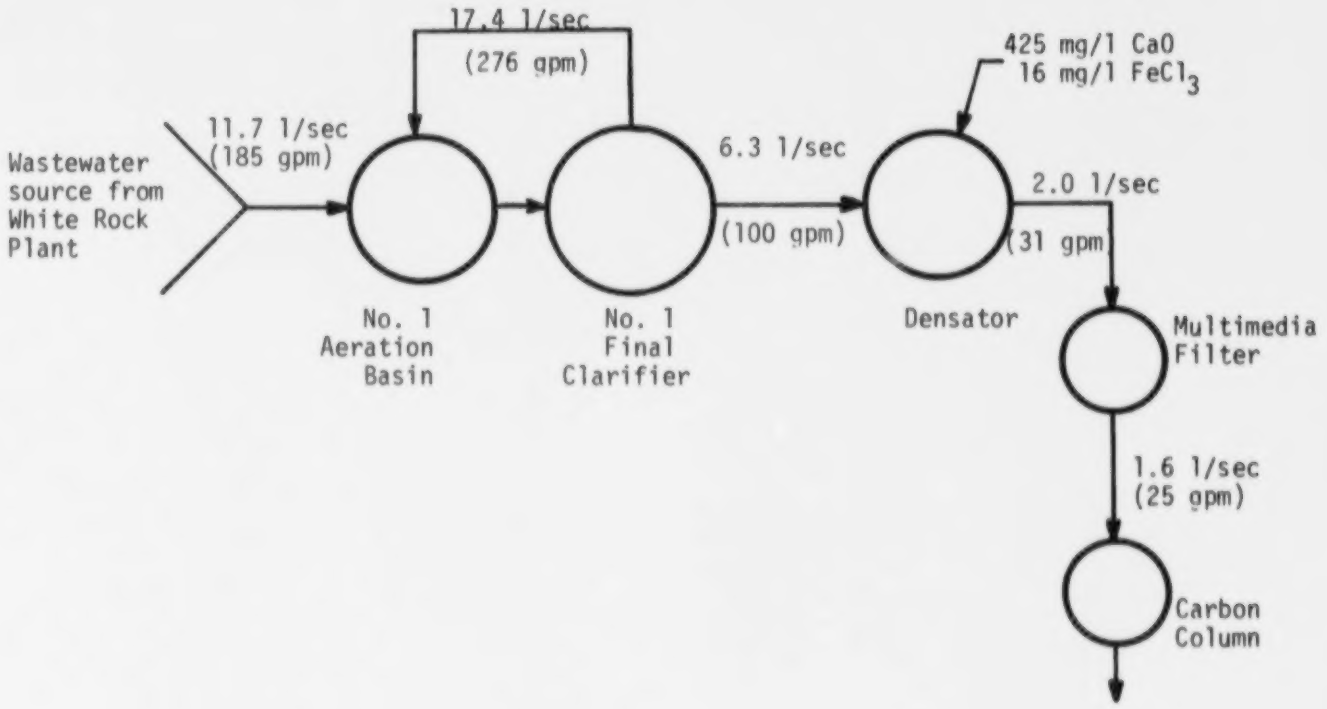

Figure 11. Process configuration: High-pH lime coagulation without recarbonation June, August-October 1972, November-December 1973

TABLE 10. SUMMARY OF WATER QUALITY DATA FOR THE HIGH-pH LIME COAGULATION STUDY

Parameter	White Rock STP Raw Wastewater (mg/1)	Final Product (mg/1)	Removal (mg/1)
COD	574	16	97.2
BOD_5	233	3	98.7
TSS	254	7	97.2
SC,μmho/cm	820	1349	N/A
TDS	532	642	N/A
NH_3-N	20.9	3.7	82.3
Org-N	13.9	1.8	87.1
NO_2+NO_3-N	0.5	9.4	N/A
pH, units	7.3	11.5	N/A
T.-Alk.(as $CaCO_3$)	214	253	N/A
P-Alk.(as $CaCO_3$)	0	228	N/A
Std. Plate Count (per ml)	--	6	N/A
Total Coliforms (per 100 ml)	--	<2	N/A
Fecal Coliforms (per 100 ml)	--	<2	N/A

*N/A =Not applicable

**-- = Not available

scaling tendency of this water was far less than anticipated, although ultimate neutralization would undoubtedly be a requirement in any similar full-scale facility.

The bactericidal effect of the high-pH lime process is evident from the final product water quality of Table 10. No bacteriological counts were run on the White Rock raw wastewater; we considered such an exercise to be unecessarily redundant. In becoming final product waters, the only disinfection process to which the wastewaters were subjected was the high-pH process.

The treatment sequence generally performed very well, and product water quality was consistently good. The COD values observed in the untreated wastewaters entering the White Rock STP and the product water at the Demonstration Plant are shown in Figure 12.

The improvement in water quality is evident. Product water COD values were stable and ranged from 0 to 25 mg/l after the early part of August 1972.

Figure 13 is a time-series plot of the effluent nitrogen concentrations (except organic nitrogen) observed during the high-pH lime coagulation portion of the research effort. It is important to note the lower and more stable COD values that result when nitrification is well advanced. The observed COD concentrations were low during the months of August-September 1972 and October, 1973. At those times nitrification was well established; however, during June 1972 product water COD concentrations as high as 40 mg/l were observed when nitrification was erratic.

COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM

The performance of the No. 1 completely-mixed activated sludge (CMAS) system is summarized in Table 11. The performance of the process can be characterized as satisfactory, but not outstanding. BOD_5 and TSS concentrations in the effluent averaged 28 and 27 mg/l, respectively; however, the effluent COD averaged 91 mg/l which was about twice the desired COD concentration of 50 mg/l.

Nitrification was not consistent, as the average of 4.4 mg/l of NH_3-N in the effluent indicates. Likewise, the effluent nitrite-nitrate nitrogen concentration was lower than one would obtain from a process that was achieving complete nitrification. The lack of a stable, nitrifying microbial population accounts for the high NH_3-N concentrations, and indirectly resulted in high effluent COD concentrations.

Table 12 summarizes the hydraulic operation of the system and more significant process control parameters. The hydraulic operation of the clarifier is very conservative by conventional design criteria, but it is a small basin that was being operated on a nitrifying system. Under these conditions conservative design and operation are necessary if adequate liquid/solids separation is to occur.

Although the combination of a sludge age of 5 days and a temperature of

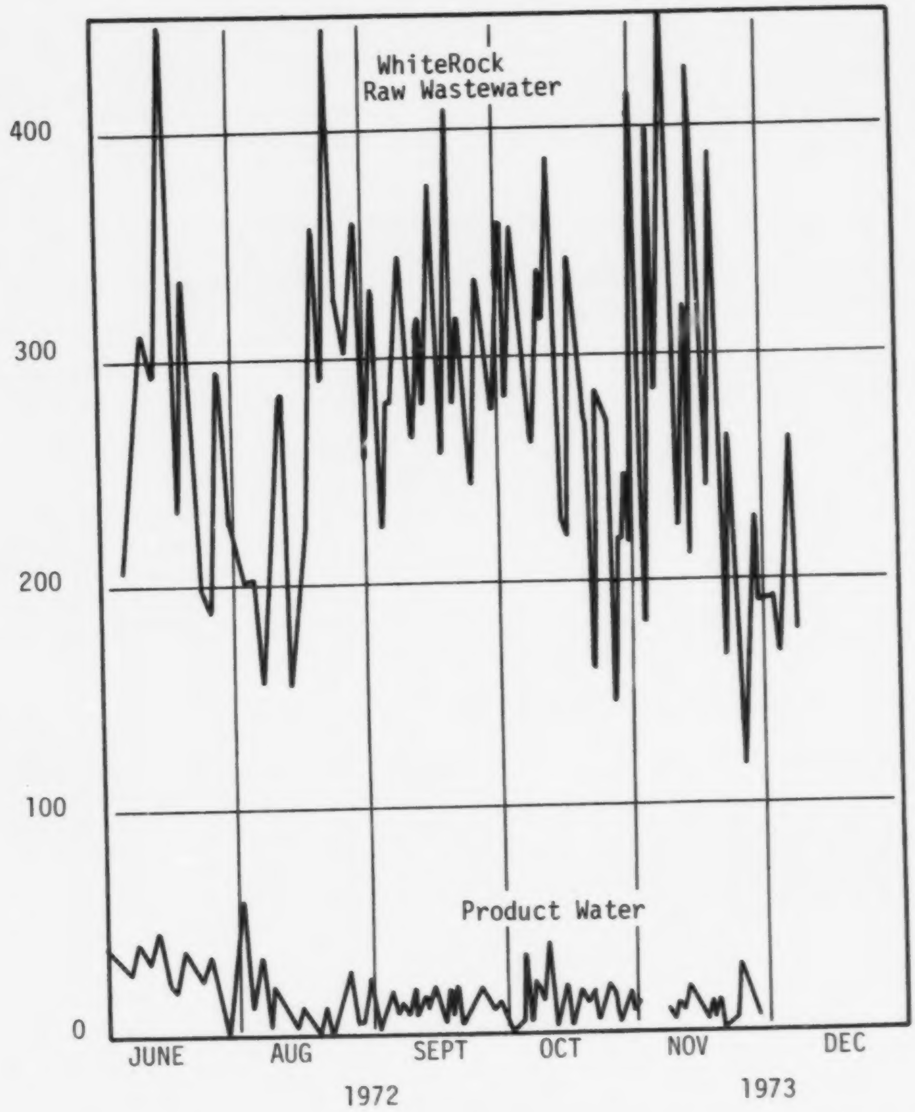

Figure 12. Raw wastewater and product water COD values observed during the high-pH lime coagulation study.

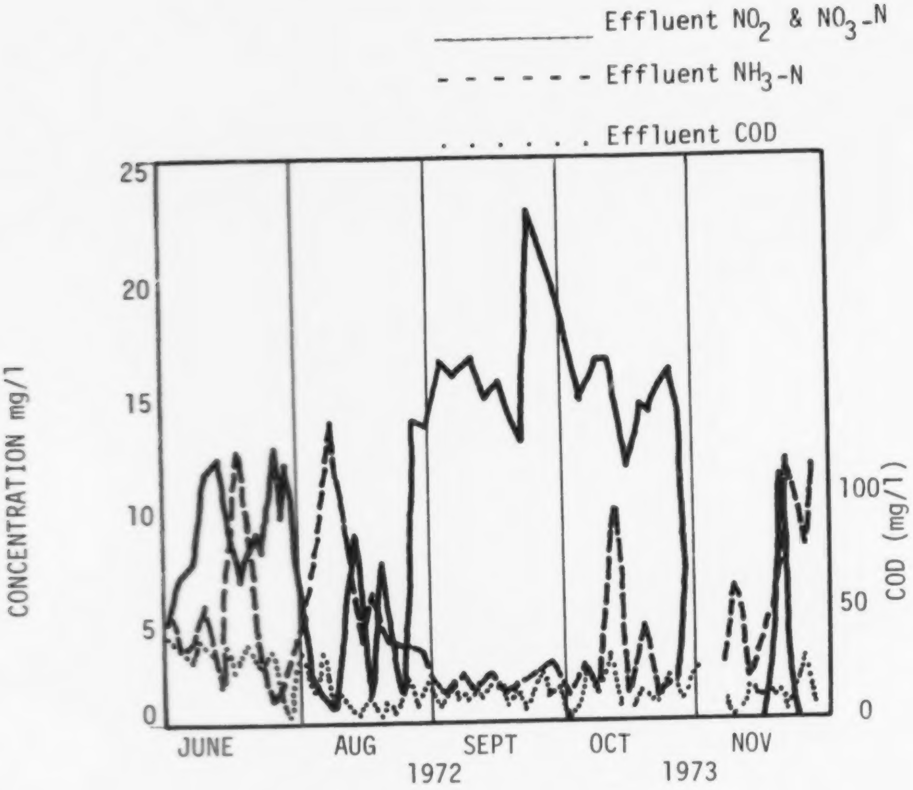

Figure 13. Effluent nitrogen concentrations observed during the high-pH lime coagulation study.

TABLE 11. PERFORMANCE SUMMARY OF THE COMPLETELY MIXED ACTIVATED SLUDGE SYSTEM HIGH-pH LIME COAGULATION STUDY.

Parameter	Activated Sludge Influent* (mg/l)	Activated Sludge Effluent (mg/l)	Reduction (percent)
COD	273	91	66.7
TOC, Soluble	42	19	54.8
BOD_5	88	28	68.2
TSS	124	27	78.2
TDS	532	541	N/A**
SC, μmho/cm	819	739	9.8
NH_3-N	16.1	4.4	72.7
Org.-N	9.5	4.9	48.4
NO_2+NO_3-N	0.77	8.2	N/A**
NO_2-N	0.06	0.59	N/A**
Total-P	11.0	9.5	13.6
pH, units	7.3	7.1	N/A**
T-Alk.(as $CaCO_3$)	210	114	45.7
P-Alk.(as $CaCO_3$)	0	0	N/A**
Std. Plate Count (per ml)	5.2×10^6	2.0×10^5	96.1
Total Coliforms (per/100 ml)	6.2×10^7	1.4×10^6	97.7
Fecal Coliforms (per 100 ml)	6.3×10^6	8.0×10^4	98.7

*White Rock effluent.
**N/A = not applicable.

TABLE 12. PROCESS SUMMARY OF THE COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM, HIGH-pH LIME COAGULATION STUDY.

HYDRAULIC OPERATION	
FLOW (Influent)	11.7 l/sec (185 gpm)
FLOW (Return)	12.0 l/sec (191 gpm)
FLOW (Waste)	12.3 m^3/day (3271 gpd)
Aeration T	1.62 hour
Clarifier overflow rate	15.4 $m^3/day/m^2$ (377 $gal/day/ft^2$)
Weir loading	36.3 m^3/day-m (2927 gal/ft-day)
Clarifier T	2.30 hours
PROCESS CONTROLS	
MLSS	2815 mg/l
MLVSS	2136 mg/l
RAS	5533 mg/l
SVI	186 mg/l
Air supplied	181. 72 l/sec (385 cfm)
D.O.	2.8 mg/l
D.O. Uptake rate	25.3 mg/l-hr
F/M (COD)	0.574 day^{-1}
F/M (SOC)	0.088 day^{-1}
F/M (BOD)	0.185 day^{-1}
Sludge Age	5.0 days
Temperature	28.3°C (83°F)

$30^{o}C$ should have been sufficient for promoting the growth of nitrifying organisms, ammonia oxidation was mediocre. It is possible that increasing the mean sludge age to approximately 8 days would have significantly improved the stability of the nitrification process.

The return sludge flow averaged 103 percent of the influent flow. The high return rate was used to keep the sludge blanket in the final clarifier as shallow as possible so that the effects of uncontrolled denitrification could be minimized. Additionally, many months of operation of the activated sludge system at the Demonstration Plant led to the conclusion that the best performance was obtained at a one to one recycle ratio.

UPFLOW CLARIFIER

The up-flow clarifier (Infilco Densator) performed as expected during the high-pH lime coagulation study. Process control and operating variables of most interest are presented in Table 13, and the performance of the process is summarized in Table 14.

An average lime dose of 425 mg/l (as CaO) was required to raise the activated sludge effluent to a pH of 11.5, and a ferric chloride dose of 16 mg/l was applied as a flocculation aid. The clarifier was operated at a conventional overflow rate of 29.0 $m^3/day\text{-}m^2$ (713 $gal/day\text{-}ft^2$). The results were good, except that the effluent TSS averaged 46 mg/l. This is higher than desired, although it had no significant impact on the subsequent filtration process. The effluent solids contained almost no volatile matter, which indicated that the solids carryover from the activated sludge system was removed in the up-flow clarifier.

The high effluent TSS concentrations observed during this portion of the study seemed inconsistent with the apparent quality of the water being produced by the Densator. The on-line surface scatter turbidimeter during this time generally indicated turbidity values less than 5 JTU, and visual examination of the water always indicated a product with good clarity. The high effluent TSS concentrations can thus be attributed to post precipitation of calcium carbonate from the high-pH effluent.

In addition to removing most of the particulate organic material, the high-pH coagulation process reduced the soluble TOC by 53 percent. Furthermore the mean organic nitrogen concentrations were reduced by 53 percent, and the ammonia nitrogen concentration was reduced from 4.4 to 2.6 mg/l. As expected, increases were observed in TDS, specific conductance, pH, and alkalinity. The effluent total phosphorus concentration averaged almost 1 mg/l, which was higher than initially anticipated, and was attributed mostly to the carryover floc in the effluent.

The microbiological data presented in Table 14 show very clearly the bactericidal effectiveness of high-pH treatment. Total coliforms were reduced by almost six logs from 1.4×10^6 to 3 per 100 ml.

TABLE 13. PROCESS SUMMARY FOR THE UP-FLOW CLARIFIER, HIGH-pH LIME COAGULATION STUDY

Q (influent)	6.3 l/sec (100 gpm)
Q (recycle)	1.8 l/sec (29 gpm)
Q (waste)	8387 l/day (2216 gpd)
Mixing T	6.6 min.
G	72 sec.$^{-1}$
Flocculation T	37 min.
G	95 sec.$^{-1}$
Settling T	3.4 hours
Clarifier overflow rate	29.1 m^3/day-m^2 (713 gal/day-ft^2)
Weir loading	32.5 m^3/day-m (2618 gal/ft-day)
Lime Dose (as CaO)	425 mg/l
$FeCl_3$ Dose	16 mg/l

TABLE 14. PERFORMANCE SUMMARY FOR THE UPFLOW CLARIFIER,HIGH-pH LIME COAGULATION STUDY.

	Activated Sludge Effluent (mg/l)	Densator Effluent (mg/l)	Reduction (percent)
COD	91	27	70.3
TOC, Soluble	19	9	52.6
BOD_5	28	4	85.7
TSS	27	46	N/A*
TDS	541	680	N/A*
SC, μmho/cm	739	1355	N/A*
NH_3-N	4.4	2.6	40.9
Org. N	4.9	2.3	53.1
NO_2+NO_3-N	8.2	9.7	N/A*
NO_2-N	0.59	0.95	N/A*
Total P	9.5	0.99	23.6
pH, units	7.1	11.5	N/A*
T-Alk. (as $CaCO_3$)	114	265	N/A*
P-Alk.(as $CaCO_3$)	0	228	N/A*
Std. Plate Count (per ml)	2.0×10^5	13	99.9935
Total Coliforms (per 100 ml)	1.4×10^6	3	99.9998
Fecal Coliforms (per 100 ml)	8.0×10^4	2	99.9975

*N/A = not applicable.

MULTIMEDIA FILTERS

The No. 1 and No. 2 filters were alternated during the project approximately monthly. During the high-pH lime coagulation portion of the study the filters were operated as shown in Table 15 , which is the process summary. The influent flow averaged 1.96 l/sec (31 gal./min.), which resulted in a filtration rate of 6.11 m/hr. (2.5 gpm/ft^2).

TABLE 15. PROCESS SUMMARY FOR THE MULTIMEDIA FILTER, HIGH-pH LIME COAGULATION STUDY

	US	METRIC
Q (influent)	31 gpm	1.96 l/sec.
Surface loading	2.5 gpm/sq.ft.	6.11 m/hr.
Average run time	39 hours	
Washwater consumption	2.28%	

This is a rather conservative filtration rate in terms of conventional wastewater treatment practice, but it closely approximates American filter operations in the water supply industry. An average run time of 39 hours resulted from this operation, which is very good considering the influent TSS concentration was 46 mg/l. The filters were backwashed when the headloss reached 10 feet.

Performance of the filters is summarized in Table 16 , and these data reflect anticipated performance. Effluent TSS are higher than the 0-2 mg/l that one should expect, but some of the solids can be explained by the post precipitation of calcium carbonate. The mean total phosphorus concentration was reduced from 0.99 to 0.41 mg/l, almost a 60-percent reduction.

ACTIVATED CARBON ADSORPTION SYSTEM

During this research effort only one of the two adsorption columns at the Demonstration Plant was in operation during any given phase of the project. In all cases the carbon was virgin (unused) at the start of each of the three phases; the spent carbon in the adjacent column was removed and replaced with virgin carbon in preparation for the next part of the project.

Process operation is summarized in Table 17 , and process performance is summarized in Table 18. The average flow of 1.6 l/sec (25 gpm) resulted in a surface loading of 4.89 m/hr. (2.0 gpm/sq.ft.). At this low surface loading and with an applied water that had already been filtered,

TABLE 16. PERFORMANCE SUMMARY FOR THE MULTIMEDIA FILTERS, HIGH-pH LIME COAGULATION STUDY.

Parameter	Densator Effluent (mg/1)	Multimedia Filter Effluent (mg/1)	Reduction (percent)
COD	27	28	N/A*
TOC, Soluble	9	--**	N/A*
BOD_5	4	4	0.0
TSS	46	12	73.9
TDS	680	642	5.6
SC,μmho/cm	1355	1384	N/A*
NH_3-N	2.6	2.2	15.4
Org.-N	2.3	2.2	4.3
NO_2+NO_3-N	9.7	9.7	0.0
NO_2-N	0.95	1.09	N/A*
Total P	0.99	0.41	58.6
pH, units	11.5	11.5	N/A*
T-Alk. (as $CaCO_3$)	265	274	N/A*
P-Alk. (as $CaCO_3$)	228	237	N/A*
Std. Plate Count (per ml)	13	8	38
Total Coliforms (per 100 ml)	3	<2	N/A*
Fecal Coliforms (per 100 ml)	2	<2	N/A*

*N/A = not applicable.
**-- = not available

headloss across the carbon column increased very slowly. The average run time between backwashes was 92 hours. The average headloss at backwashing was about 3.5 feet, therefore, the backwash of the carbon columns was principally a function of convienience for the operating personnel and was not dictated by process hydraulics.

TABLE 17. PROCESS SUMMARY FOR THE ACTIVATED CARBON ADSORPTION SYSTEM, HIGH-pH LIME COAGULATION STUDY.

Q (influent)	1.61 l/sec (25 gpm)
Surface loading	4.89 m/hr. (2.0 gpm/sq.ft.)
Empty-bed contact time	37 minutes
Average run time	92 hours
Washwater consumption	2.01%

The empty-bed contact time of 37 minutes resulted in a COD reduction of almost 43 percent, which corresponds to a product water COD of 16 mg/l. Effluent TSS averaged 7 mg/l, which seemed inordinately high since the water had been filtered through 91.4 cm (36 inches) of filtering media followed by 3.1 meters (10 feet) of granular activated carbon. Therefore, the presence of a TSS concentration of 7 mg/l in the effluent seemed very unlikely. The average turbidity of the product water was 0.4 NTU which is not indicative of 7 mg/l TSS. Post precipitation of calcium carbonate in the high-pH effluent was determined to be the cause of the apparently high TSS values.

The decrease in alkalinity that was observed across the carbon column is significant. After this portion of the project was concluded layers about 0.7 meter (2.5 ft.) thick at both the top and bottom of the column were found to be cemented together with calcium carbonate. Shovels and picks were required to break-up the carbon for removal from the column. The direct filtration or adsorption of high-pH waters was necessary, but very undesirable, during this phase of the project, but the alkalinity data did indicate that the problem was developing.

After this problem was discovered the backwash frequency was increased to every other day. Additionally, the duration of the air scour was increased from 2 to 5 minutes. Neither of these actions was sufficient to break-up the encrusted carbon. No increases in headloss were observed at the time the encrustation occurred, which indicates that the carbon's porosity was not affected significantly.

TABLE 18. PERFORMANCE SUMMARY FOR THE ACTIVATED CARBON ADSORPTION SYSTEM, HIGH-pH LIME COAGULATION STUDY.

Parameter	Multimedia Filter Effluent (mg/l)	Carbon Column Effluent (mg/l)	Reduction (percent)
COD	28	16	42.9
TOC, Soluble	—*	6	N/A**
BOD_5	4	3	25.0
TSS	12	7	41.7
TDS	642	642	0.0
SC, µmho/cm	1384	1349	2.5
NH_3-N	2.2	3.7	N/A**
Org.-N	2.2	1.8	18.2
NO_2+NO_3+-N	9.7	9.4	3.1
NO_2-N	1.09	1.28	N/A**
Total P	0.41	0.16	61.0
pH, units	11.5	11.5	N/A**
T-Alk. (as $CaCO_3$)	274	253	7.7
P-Alk. (as $CaCO_3$)	237	228	4.0
Standard Plate Count (per ml)	8	6	25.0
Total Coliforms (per 100 ml)	<2	<2	N/A**
Fecal Coliforms (per 100 ml)	<2	<2	N/A**

*Not available.

**Not applicable.

METAL REMOVALS

Metals data during the period of operation on lime without recarbonation can be found in Tables 19 through 23 summarizing the activated sludge influent, activated sludge effluent, upflow clarifier effluent, filter effluent, and carbon column effluent samples, respectively.

Silver

Silver is present in Dallas'wastewater only at extremely low levels, too low in fact to confidently assess its behavior during treatment. Detectable amounts were measured in only 18 percent of the train influent samples and 26 percent of the train effluent samples. For an undetermined reason most of the detectable silver appeared during the month of August 1972. Silver was removed by the activated sludge, filtration, and carbon adsorption processes, but was apparently increased by the chemical treatment process. In view of the paucity of samples containing measurable concentrations of silver, it is difficult to justify the increase as being an actual occurrence. However, the removals perfectly balance the increase, and the net change through the train is zero. At the low concentrations there appears to be no significant removal of silver.

The probability distributions for silver in the activated sludge influent and the carbon column effluents are presented in Figure 14. The MCL (maximum contaminant level) of the NIPDWR (National Interim Primary Drinking Water Regulations) is also shown.

Aluminum

Mean removals of 59 percent and 47 percent were obtained for aluminum through the activated sludge and chemical treatment processes, respectively. The apparent increase through the filter and carbon column is based on a single sample set collected on November 27th. The lack of sufficient data for aluminum on this particular treatment sequence precludes further comment.

Arsenic

The slight increase in arsenic through biological treatment appears to be a random pattern. The biggest removals occurred in the upflow clarifier, 44 percent based on the mean and 61 percent based on the median. The reductions were proportional to the influent concentrations (r=0.86).

A removal of 35 percent (mean) or 28 percent (median) occurred through the multimedia filter; the reduction was proportional to the influent concentrations (r=0.90). A removal of only 9 percent (mean) to 14 percent (median) occurred through carbon filtration; the reduction exhibiting a moderate concentration effect (r=0.53). Overall removal of arsenic through the treatment train was 66 percent (mean) and 70 percent (median). The drinking water limit for arsenic of 0.05 mg/l was exceeded on only 4 percent of the train influent samples, and none of the effluent samples.

TABLE 19. ACTIVATED SLUDGE INFLUENT METALS SUMMARY HIGH-pH LIME COAGULATION STUDY JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

	MEDIAN	GEO MEAN	ARITH MEAN	σ	MAX	MIN	N
Ag*	0.0	0.31	0.62	1.92	10.0	0.0	34
Al	0.73	0.84	0.92	0.46	1.60	0.54	6
As*	14.5	14.8	18.7	13.4	51.5	3.6	28
B	0.42	0.38	0.39	0.091	0.52	0.20	28
Ba	0.130	0.126	0.149	0.083	0.42	0.01	44
Ca	40.0	43.8	45.0	11.7	80.0	34.0	66
Cd*	10.0	9.0	13.3	13.2	79.0	0.0	68
Co	0.040	0.040	0.045	0.021	0.110	0.010	43
Cr	0.190	0.193	0.209	0.092	0.62	0.07	68
Cu	0.069	0.048	0.138	0.205	1.04	0.0	66
Fe	1.00	1.00	1.05	0.31	1.86	0.43	66
Hg*	0.50	0.38	0.53	0.46	1.95	0.0	23
K	14.9	14.7	14.7	0.97	16.2	12.3	34
Mg	5.21	5.23	5.27	0.64	7.16	3.09	56
Mn	0.070	0.69	0.071	0.017	0.13	0.05	66
Mo*	2.0	2.3	2.5	1.9	5.0	0.0	10
Na	110.0	107.2	108.8	17.8	148.0	57.0	43
Ni	0.090	0.089	0.104	0.060	0.28	0.03	43
Pb	0.100	0.088	0.100	0.057	0.45	0.02	65
Se*	11.0	8.0	14.2	11.9	40.0	0.0	23
Si	9.0	9.5	10.0	3.7	17.0	6.4	6
Sr	0.26	0.27	0.27	0.044	0.33	0.23	6
V*	3.6	4.1	4.6	2.7	8.5	2.8	4
Zn	0.305	0.299	0.323	0.14	0.88	0.12	66

Note:0 = std. deviation Concentration in mg/l
MAX = Maximum
MIN = Minimum *μg/l
N = Number of samples
GEO MEAN = Geometric Mean
ARITH MEAN = Arithmetic Mean

TABLE 20. ACTIVATED SLUDGE EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

	MEDIAN	GEO MEAN	ARITH MEAN	σ	MAX	MIN	N
Ag*	0.0	0.27	0.26	0.75	3.0	0.0	34
Al	0.35	0.33	0.38	0.22	0.78	0.16	6
As*	18.0	12.6	19.5	17.2	68.0	0.3	27
B	0.43	0.41	0.42	0.077	0.57	0.17	28
Ba	0.075	0.065	0.079	0.050	0.29	0.0	44
Ca	38.7	41.4	42.5	10.7	76.0	26.5	66
Cd*	7.0	6.0	7.6	5.1	22.0	0.0	68
Co	0.040	0.029	0.037	0.020	0.10	0.0	43
Cr	0.070	0.072	0.085	0.068	0.56	0.013	68
Cu	0.050	0.050	0.080	0.115	0.69	0.01	66
Fe	0.29	0.30	0.34	0.19	1.31	0.10	66
Hg*	0.18	0.18	0.29	0.42	1.90	0.0	23
K	14.3	14.3	14.3	0.90	16.2	12.4	34
Mg	4.98	4.93	4.97	0.63	6.60	2.43	56
Mn	0.050	0.047	0.051	0.017	0.096	0.010	66
Mo*	1.5	1.7	2.1	2.0	5.0	0.0	10
Na	108.0	106.7	108.1	17.1	150.0	57.0	43
Ni	0.074	0.064	0.082	0.047	0.200	0.0	43
Pb	0.030	0.033	0.044	0.042	0.300	0.0	65
Se*	2.0	1.7	2.4	2.4	9.0	0.0	23
Si	9.6	9.2	9.6	2.9	13.5	4.6	6
Sr	0.24	0.24	0.24	0.03	0.29	0.20	6
V*	3.2	3.7	4.2	2.6	8.0	2.4	4
Zn	0.100	0.109	0.123	0.079	0.45	0.05	66

Concentration in mg/l

*μg/l

TABLE 21. UP-FLOW CLARIFIER EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

	MEDIAN	GEO MEAN	ARITH MEAN	σ	MAX	MIN	N
Ag*	0.0	0.42	0.94	2.00	10.0	0.0	34
Al	0.19	0.19	0.20	0.077	0.30	0.13	4
As*	7.0	6.6	10.8	11.3	46.5	0.0	24
B	0.42	0.40	0.41	0.077	0.57	0.22	27
Ba	0.065	0.061	0.083	0.062	0.270	0.0	42
Ca	153.0	148.5	156.1	49.3	313.0	53.0	64
Cd*	7.5	5.0	7.6	5.5	20.0	0.0	66
Co	0.050	0.053	0.058	0.027	0.130	0.020	41
Cr	0.010	0.006	0.012	0.013	0.060	0.0	66
Cu	0.029	0.023	0.056	0.121	0.770	0.0	64
Fe	0.18	0.22	0.30	0.36	2.44	0.07	64
Hg*	0.13	0.13	0.14	0.15	0.62	0.0	23
K	14.5	14.4	14.5	1.1	17.4	12.7	34
Mg	0.66	0.77	0.99	0.89	4.68	0.29	54
Mn	0.010	0.003	0.010	0.011	0.050	0.0	64
Mo*	3.4	3.0	4.2	3.5	11.5	1.0	10
Na	110.0	114.7	117.3	27.4	200.0	82.0	41
Ni	0.040	0.031	0.052	0.042	0.163	0.0	41
Pb	0.040	0.032	0.039	0.027	0.100	0.0	63
Se*	0.7	1.7	1.9	2.5	10.0	0.0	23
Si	13.1	12.1	13.4	6.6	20.0	7.2	4
Sr	0.23	0.22	0.23	0.07	0.32	0.15	4
V*	3.3	3.4	3.6	1.3	5.3	2.6	4
Zn	0.030	0.028	0.063	0.121	0.68	0.0	64

Concentration in mg/l
*μg/l

TABLE 22. FILTER EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

	MEDIAN	GEO MEAN	ARITH MEAN	σ	MAX	MIN	N
Ag*	0.0	0.41	0.94	2.1	10.0	0.0	33
Al	N/A	0.29	0.29	N/A	N/A	N/A	1
As*	5.0	3.5	7.0	7.6	30.0	0.0	21
B	0.43	0.41	0.41	0.075	0.55	0.20	23
Ba	0.070	0.067	0.092	0.067	0.23	0.0	38
Ca	145.5	147.8	156.1	51.0	308.0	43.0	60
Cd*	7.0	5.0	7.4	5.2	24.0	0.0	61
Co	0.050	0.050	0.057	0.030	0.13	0.02	37
Cr	0.005	0.004	0.009	0.013	0.05	0.0	61
Cu	0.037	0.032	0.066	0.125	0.77	0.0	60
Fe	0.07	0.08	0.12	0.14	0.68	0.01	60
Hg*	0.065	0.11	0.094	0112	0.43	0.0	20
K	14.3	14.6	14.7	1.8	23.0	12.6	33
Mg	0.46	0.52	0.66	0.56	2.96	0.22	51
Mn	0.0	0.001	0.0061	0.0084	0.04	0.0	60
Mo	2.0	1.8	1.7	1.6	4.6	0.0	9
Na	112.0	114.9	117.1	24.6	187.0	80.0	37
Ni	0.030	0.020	0.042	0.038	0.153	0.0	37
Pb	0.030	0.031	0.040	0.032	0.20	0.0	58
Se*	1.75	1.4	2.04	1.97	6.5	0.0	20
Si	N/A	6.7	6.7	N/A	N/A	N/A	1
Sr	0.22	0.21	0.23	0.09	0.32	0.14	3
V*	N/A	2.4	2.4	N/A	N/A	N/A	1
Zn	0.030	0.025	0.048	0.076	0.45	0.0	60

Concentration in mg/l

*µg/l

N/A: Not Applicable

TABLE 23. CARBON COLUMN EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST–OCTOBER 1972, NOVEMBER-DECEMBER 1973

	MEDIAN	GEO MEAN	ARITH MEAN	σ	MAX	MIN	N
Ag*	0.0	0.37	0.62	1.21	4.0	0.0	34
Al	N/A	0.36	0.36	N/A	N/A	N/A	1
As*	4.3	3.1	6.4	6.8	22.14	0.0	21
B	0.38	0.37	0.39	0.13	0.85	0.17	23
Ba	0.080	0.072	0.091	0.060	0.24	0.01	39
Ca	138.0	136.2	144.9	49.4	286.0	39.0	61
Cd*	7.0	5.0	7.2	5.0	24.0	0.0	62
Co	0.050	0.047	0.054	0.026	0.133	0.010	38
Cr	0.010	0.005	0.0095	0.0103	0.030	0.0	62
Cu	0.026	0.027	0.071	0.149	0.77	0.0	61
Fe	0.050	0.05	0.064	0.045	0.19	0.01	61
Hg*	0.04	0.10	0.11	0.17	0.70	0.0	20
K	14.3	14.4	14.5	1.4	19.0	12.1	34
Mg	0.37	0.45	0.58	0.53	2.79	0.19	52
Mn	0.0040	0.002	0.0067	0.0081	0.040	0.0	61
Mo*	2.0	1.8	1.9	1.7	6.0	0.0	10
Na	109.0	115.0	117.5	26.8	195.0	84.0	38
Ni	0.020	0.013	0.029	0.032	0.155	0.0	38
Pb	0.040	0.035	0.043	0.025	0.10	0.0	59
Se*	0.21	1.0	1.00	1.42	4.5	0.0	20
Si	N/A	8.8	8.8	N/A	N/A	N/A	1
Sr	0.28	0.22	0.23	0.10	0.30	0.12	3
V*	N/A	2.9	2.9	N/A	N/A	N/A	1
Zn	0.030	0.018	0.041	0.071	0.45	0.0	61

Concentration in mg/l

*μg/l

N/A : Not Applicable

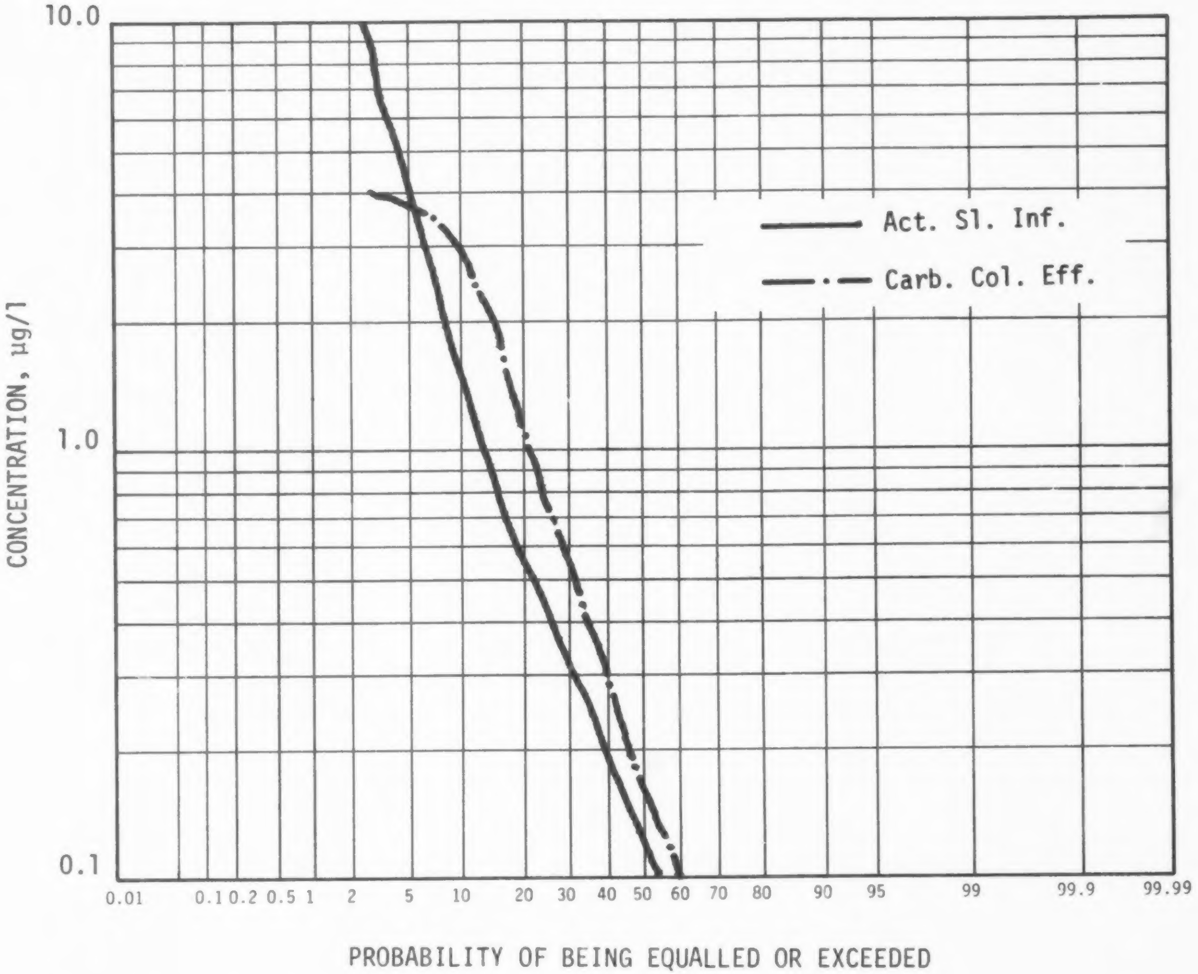

Figure 14. Frequency distributions for silver, high-pH lime coagulation study.

Probability distributions are presented for arsenic at various points in the treatment sequence in Figure 15.

Boron

Boron was refractory to the high-pH lime treatment train, and the mean observed influent and effluent concentrations were the same. The only sustained removals occurred in the carbon column, and even then the boron reduction was only 6 percent (mean) or 12 percent (median). However, virgin carbon removed more boron than partially saturated carbon. The removals were found to be inversely proportional to the unit COD loading on the carbon (X/M value).

Barium

The greatest barium removal occurred in the activated sludge unit, which achieved 47 percent (mean) and 42 percent (median) reductions. A slight increase was noted in the Densator, the most likely source being contamination within the commercial hydrated lime. Barium, a Group II element, is often not extracted during the refining of native lime. Although the barium content of the lime shipments was not determined, it would probably have been at least 0.05 percent, the average concentration found in the Earth's crust (9). Using this value, there could have been an increase of 0.21 mg/l barium through the Densator, yet the observed increase was only 0.004 mg/l; hence, some removal is suggested. There was a concentration-dependent reduction of barium (r=0.55) in the upflow clarifier at influent concentrations greater than about 0.05 mg/l. Removals by filtration and carbon adsorption were minor, and no significant patterns could be identified.

Probability distributions for treatment sequence influent and effluent concentrations are presented in Figure 16.

Calcium

A large amount of calcium was imparted to the wastewater during the high-pH lime treatment, and no positive removals of any significance were observed. The average lime dose of 425 mg/l as CaO represents a gross addition of approximately 303 mg/l as calcium. Since the observed increase through the upflow clarifier was 114 mg/l or 38 percent of the amount added, it would appear that the remaining 62 percent precipitated as sludge. A considerable portion of the calcium in the Densator effluent could have been present in a divalent ionic state (Ca^{++}) as opposed to $CaCO_3$, since no change in the calcium concentration occurred after filtration. Oddly enough, there was very little evidence of scale buildup in the piping, filter plenums, pumps, etc. downstream of the Densator, with the notable exception of the granular carbon, where visible scale accumulation on the carbon surface was observed. The total alkalinity was reduced an average of 21 mg/l as $CaCO_3$, and the observed decrease in calcium concentration as a result of carbon adsorption was 11.2 mg/l. During the three-month period from August through October 1972, starting with virgin carbon, a calculated total of 236 lb. of calcium was deposited on the bed. The only parameter which

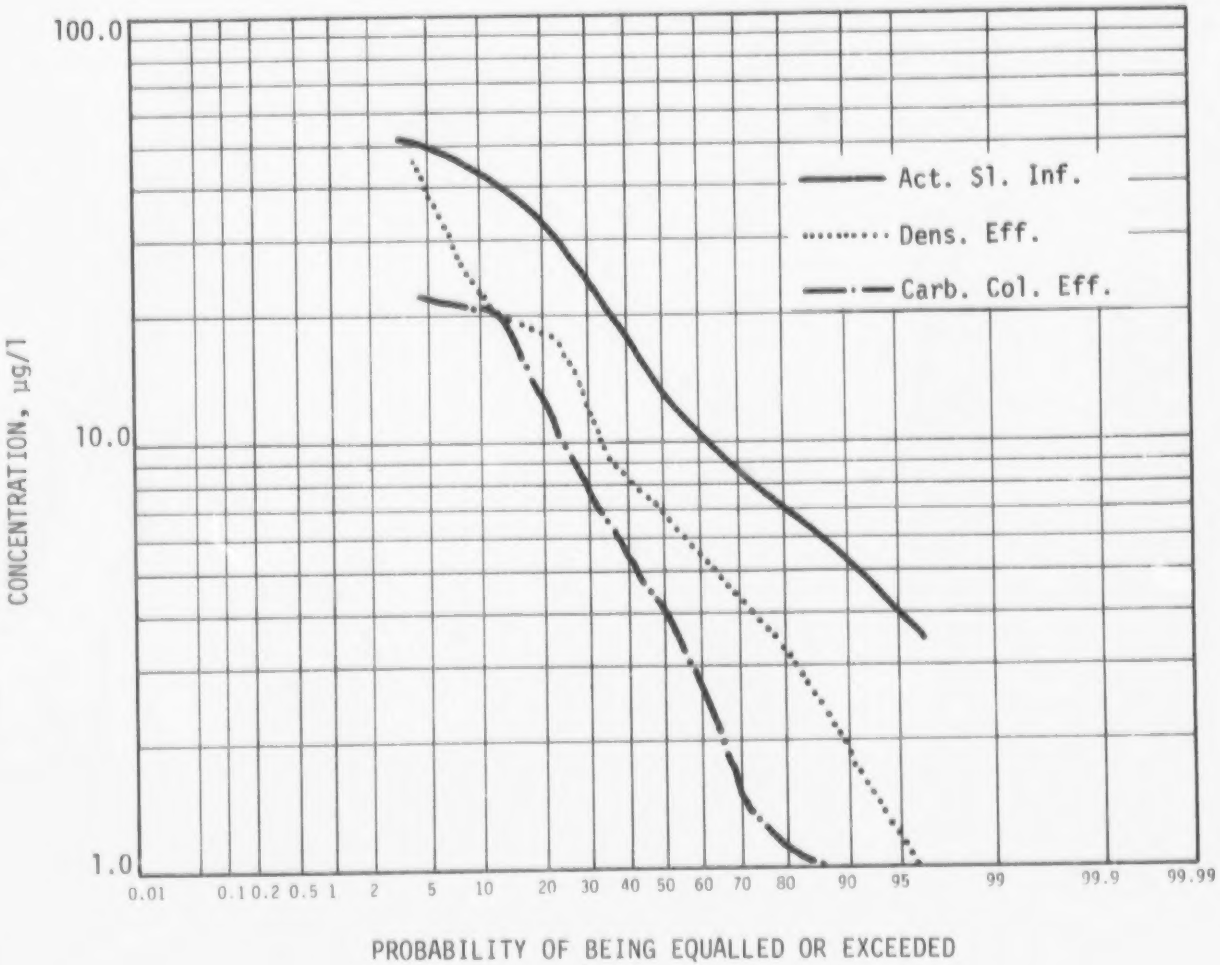

Figure 15. Frequency distributions for arsenic, high-pH lime coagulation study.

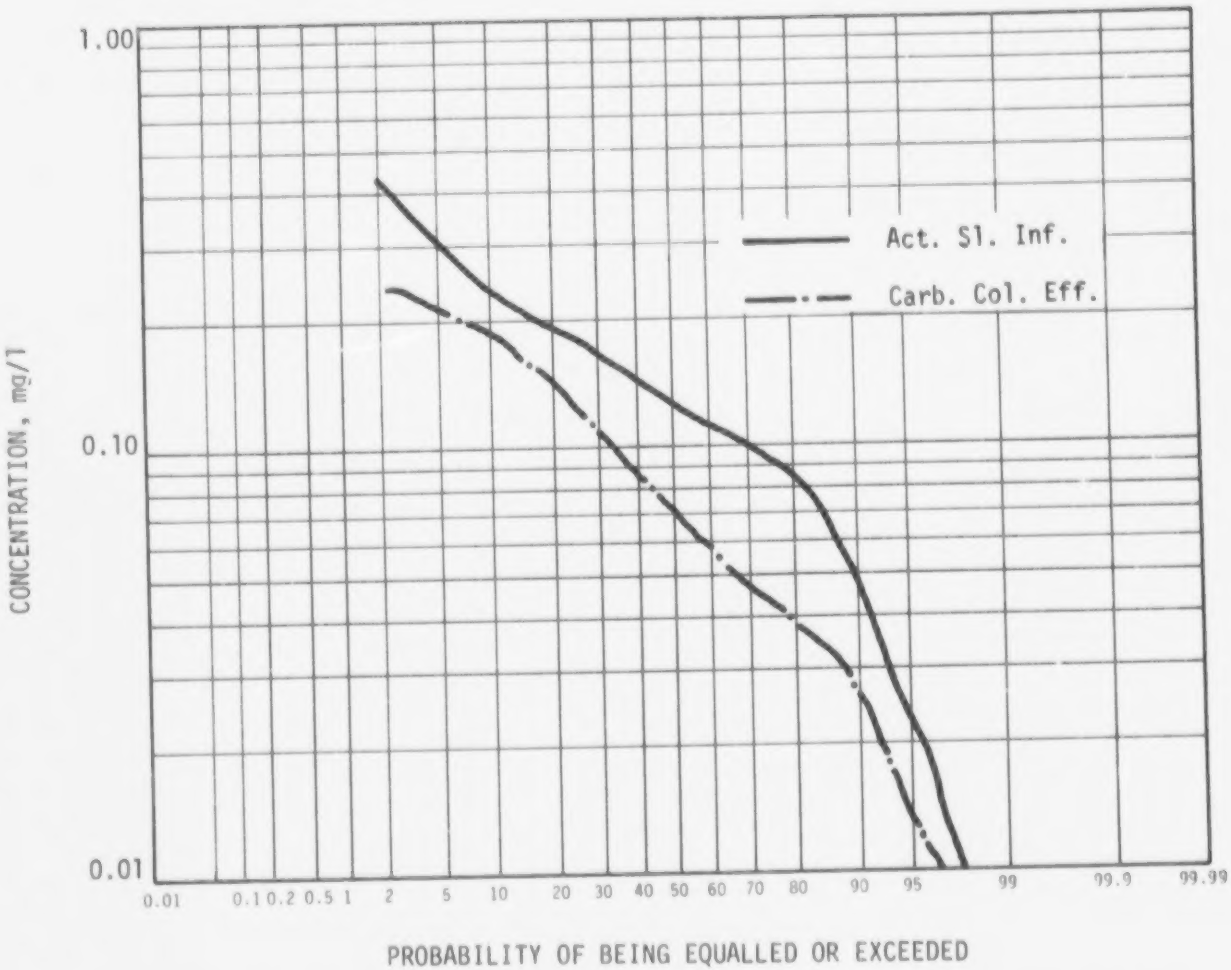

Figure 16. Frequency distributions for barium, high-pH lime coagulation study.

correlated with calcium was suspended solids, particularly in the multimedia filter effluent. TSS reductions through the filter also showed a negative correlation with calcium. The net effect of the treatment train, then, was the addition of about 100 mg/l calcium to the water.

Cadmium

The highest removals of cadmium occurred during biological treatment, 43 percent (mean) and 30 percent (median). Subsequent physical/chemical treatment removed only an additional 5 percent (mean), and zero removal on the basis of the medians. The reductions resulting from physical/chemical treatment processes exhibited a strong concentration effect (r=0.95), and were moderately proportional to the lime dose, and inversely proportional to effluent turbidity, TSS and total P. No significant removal patterns were observed in the multimedia filters, but a moderate concentration effect was seen on the carbon columns. In spite of the above mentioned removal patterns, the observed removals were not sufficient for consistently achieving the maximum contaminant level (MCL) of 0.01 mg/l as promulgated in the National Interim Primary Drinking Water Regulations (NIPDWR). Approximately 46 percent of the train influent samples and 21 percent of the train effluent samples exceeded this limit, the highest observed train effluent concentration out of 62 composite samples being 0.024 mg/l.

The frequency distributions for observed cadmium concentrations in the treatment sequence influent and effluent are shown in Figure 17. The median concentration decreased approximately 0.003 mg/l as a result of treatment, which would indicate that cadmium was relatively unaffected by the treatment processes employed during this phase of the project.

Cobalt

Cobalt was one of the refractory metals in the treatment train. Although the mean concentration dropped 16 percent during biological treatment, the influent and effluent median concentrations were the same. Attention is called to the increase in cobalt concentration resulting from chemical treatment, most likely originating from trace quantities within the lime and ferric chloride slurries. There was, in fact, a positive correlation between the chemical dose and cobalt concentration, but no removal patterns were observed. The net median increase through the train was 0.010 mg/l.

The probability distributions of the influent and effluent cobalt concentrations shown in Figure 18 reflect its very refractory nature.

Chromium

The mean and median removals of chromium were 59 and 63 percent through the activated sludge unit, and 86 percent in the Densator. Reductions in the latter exhibited a strong concentration effect (r=0.99), and were inversely proportional to total phosphorus concentration in the process effluent. Multi-media filtration removed an additional 24 percent (mean) or

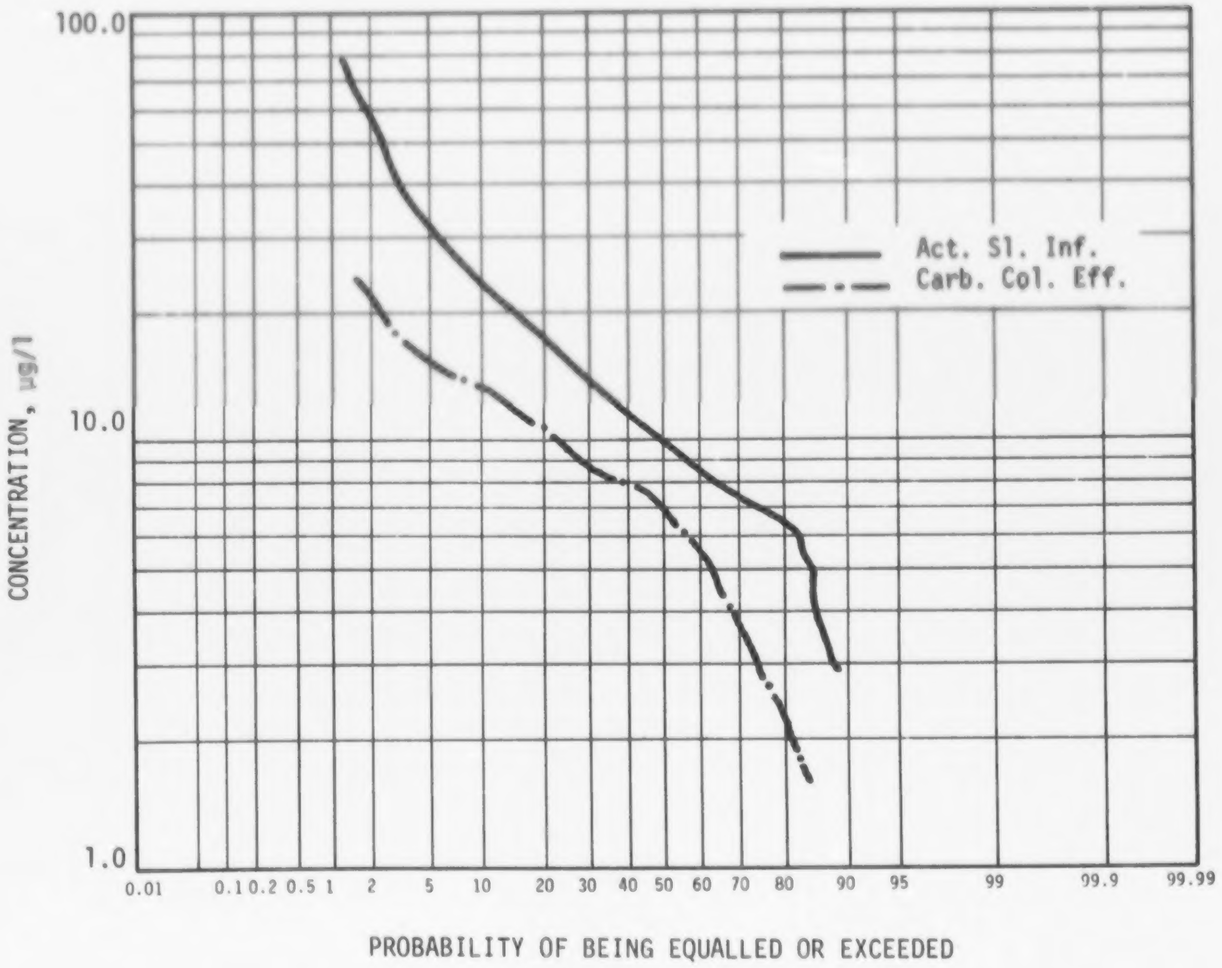

Figure 17. Frequency distributions for cadmium,high-pH lime coagulation study.

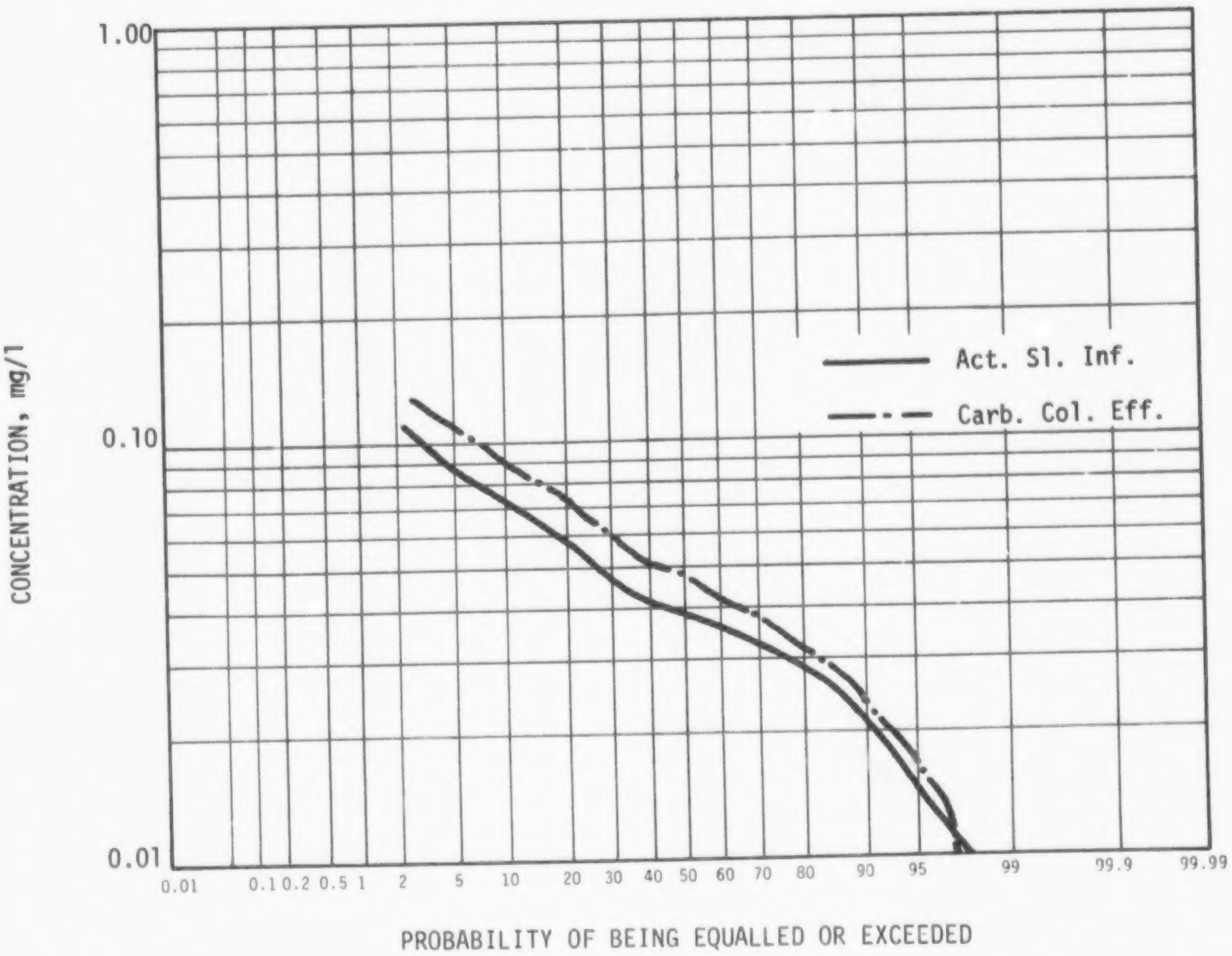

Figure 18. Frequency distributions for cobalt, high-pH lime coagulation study.

50 percent (median), while subsequent carbon filtration failed to remove any chromium. All of the train influent samples exceeded the drinking water MCL of 0.05 mg Cr/l, while only 3 percent of the Densator effluent samples and none of the train effluent samples exceeded the limit.

As the data in Figure 19 clearly indicate, chromium was effectively removed by the treatment sequence used. It is significant to note that the biological process was very effective in removing chromium.

Copper

Most of the copper was removed by the activated sludge and high-pH lime treatment, with little or no subsequent removal through filtration and carbon adsorption processes. A removal of 42 percent (mean) or 28 percent (median) occurred through the activated sludge process, and a 30 percent (mean) or 41 percent (median) removal occurred in the Densator. Reduction in copper by high-pH lime clarification exhibited a concentration effect, and was proportional to both the effluent methyl orange and phenolphthalein alkalinities. However, removals were poor when effluent turbidity exceeded about 3 NTU. During filtration, the mean and median concentration increased by 18 percent and 28 percent, respectively. The reason for the observed increase in copper concentrations has not been positively identified, however, corrosion of bronze piping appurtenances seems to be the plausible explanation.

Iron

Each unit in the high-pH lime treatment train significantly reduced the concentration of iron. Approximately 72 percent of the total iron removed by the treatment sequence was effected in the activated sludge unit, with mean and median removals of 67 percent and 71 percent, respectively. The Densator removed an additional 12 percent (mean) and 40 percent (median), the reductions exhibiting a concentration effect. Occasionally turbidity and suspended solids breakthroughs in the filters caused a decline in iron removal. On average, the multimedia filters removed about four times as much iron as the Densator, with mean and median removal efficiencies of 59 percent and 60 percent, respectively. The reductions exhibited a strong concentration effect (r=0.997), although there was no correlation with suspended solids or turbidity. Removal by carbon adsorption averaged 48 percent (mean) and 29 percent (median), exhibiting a strong concentration effect (r=0.95). It would appear that extreme values were damped better in the carbon column than in the multimedia filter. The Secondary Drinking Water Regulation recommends a MCL of 0.3 mg/l, and this concentration was exceeded by all of the train influent samples and none of the train effluent samples.

Mercury

Mercury was effectively removed by each process in the treatment train. Removal through the activated sludge unit averaged 45 percent and 64 percent based on the mean and median values, the respective Densator removals

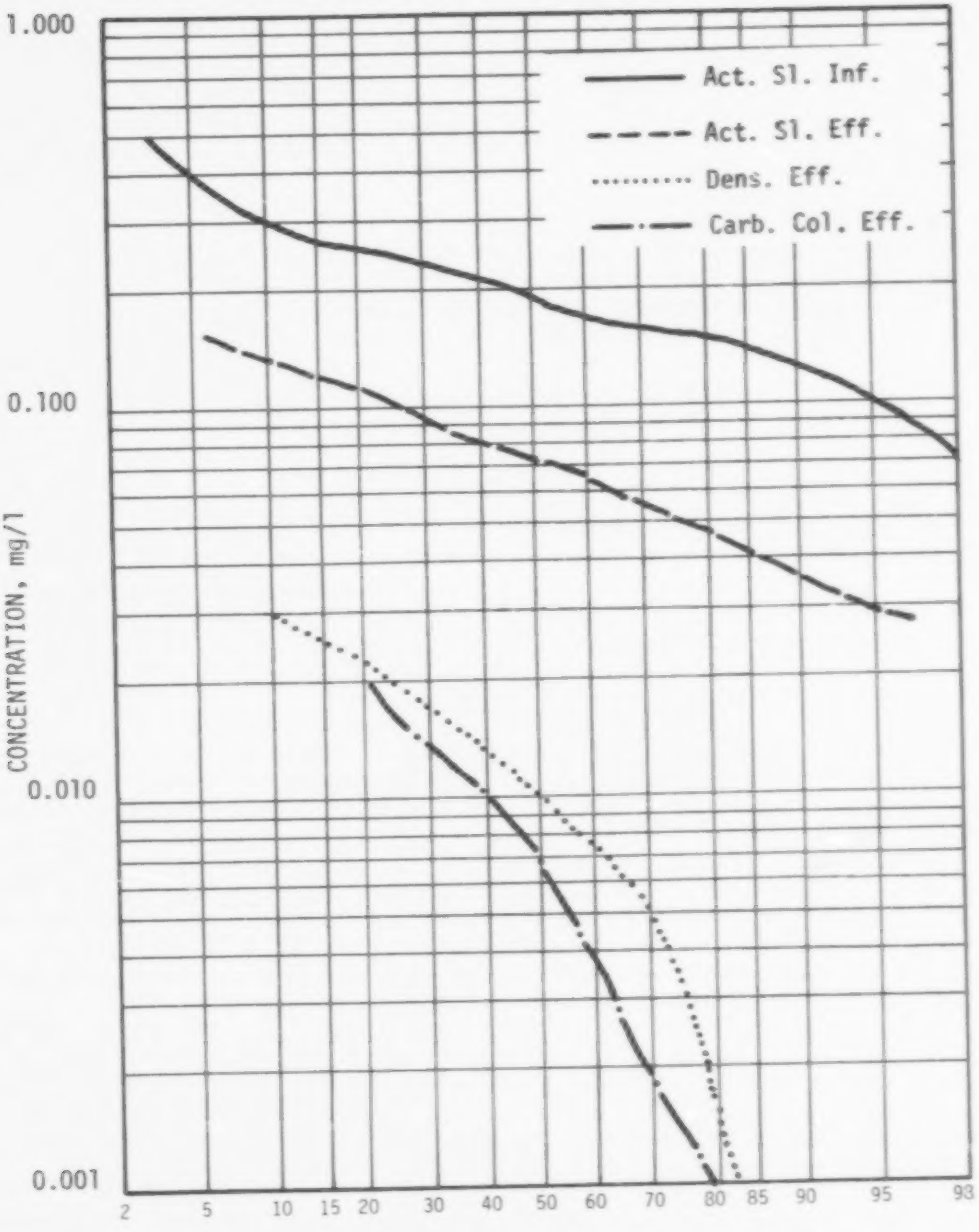

Figure 19. Frequency distributions for chromium, high-pH lime coagulation study.

being 51 percent and 31 percent. Reductions through the Densator exhibited a concentration effect (r=0.86). Mean and median removals through the multimedia filters were 35 percent and 48 percent, respectively, the reductions exhibiting a concentration effect (r=0.80). The mean concentration of mercury increased by 17 percent through the carbon column, but the median concentration declined by 38 percent. Although the influent and effluent distribution patterns are very similar, the effluent skews slightly more toward the high side, which would explain the inequity between the mean and median removals. Reductions through the carbon column exhibited a nonlinear concentration effect, with a cut-off reduction of around 0.15 μg/l. The maximum train influent concentration was only 1.95 μg/l, just below the MCL of 2.0 μg/l established in the NIPDWR. Consequently, the train effluent quality was well within the limitation established for drinking water.

Frequency distributions for selected points in the Pilot Plant processing are presented in Figure 20.

Potassium

As anticipated potassium was not significantly removed by any of the unit processes. The greatest removals occurred in the activated sludge system, 2.5 percent by means and 4.0 percent by median. The remaining units in the treatment train effected only minor, and probably random, changes in the concentration.

Magnesium

Removal of magnesium through the activated sludge unit was only 5 percent (mean) or 4 percent (median), compared to 80 percent (mean) or 87 percent (median) through the Densator. The probability distribution pattern of magnesium was significantly altered as a result of chemical treatment, and the reductions through the Densator exhibited a concentration effect (r=0.56). Effluent turbidity and suspended solids were a fair measure of the amount of magnesium in the effluent, accompanied, however, by a few larger variations. Effluent total P concentration correlated well with effluent magnesium (r=-0.69), while the reductions were found to correlate with both effluent TSS (r=0.50) and total P (r=0.70).

Removal of magnesium by filtration averaged 34 percent (mean) or 30 percent (median). The reductions exhibited a linear concentration effect (r=0.78), increasing sharply with suspended solids removals of 90 percent or more. The reductions also decreased as the filter effluent TSS and turbidity increased.

Carbon filtration effected removals of 11 percent (mean) or 21 percent (median), the reductions exhibiting a concentration effect (r=0.48). Probability distributions on the Densator, filter, and carbon effluents were quite similar, all skewed toward high concentrations, as opposed to the log-normal pattern of the activated sludge effluent and influent distributions.

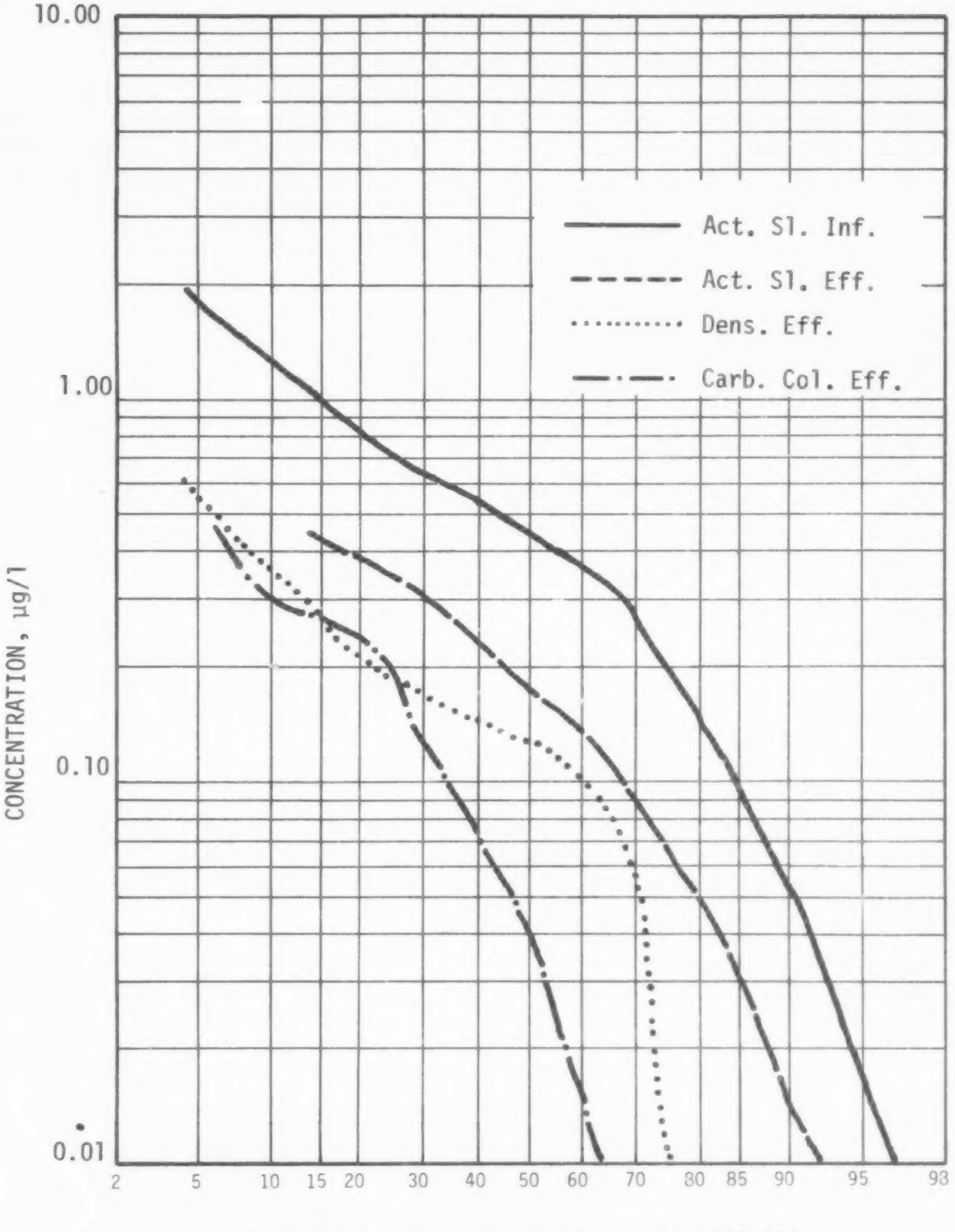

Figure 20. Frequency distributions for mercury, high-pH lime coagulation study.

Manganese

The activated sludge unit removed 28 percent (mean) or 29 percent (median) of the influent manganese, but the biggest removals were observed as a result of chemical treatment, 80 percent of both the mean and median values. Reductions through the Densator exhibited a strong linear concentration effect (r=0.94), but failed to correlate with other water quality parameters. The median filter effluent concentration was zero; however, the removal of manganese, based on mean values, was about 40 percent. Although non-linear, the reductions through the filter exhibited a concentration effect (r=0.71), and were inversely proportional to effluent TSS. There was no removal of manganese across the carbon column. The Densator caused a major shift in the distribution of concentrations, and singly achieved about 2/3 of the total train reduction. The MCL of 0.05 mg/l was exceeded by 86 percent of the activated sludge influent samples, 44 percent of the activated sludge effluent samples, but none of the succeeding samples in the treatment train.

Molybdenum

The activated sludge removals of molybdenum were 16 percent (mean) and 25 percent (median). However, the concentrations increased through the Densator by about 0.002 mg/l, originating probably from contamination in the lime. A removal of 59 percent (mean) or 41 percent (median) through the multimedia filters essentially counteracted the increase. The reductions through the filters exhibited a concentration effect (r=0.89) and possibly a correlation with several other parameters; however, the paucity of data precluded conclusive analysis.

The totally refractory behavior of molybdenum is clearly evident in Figure 21, which presents the probability distribution functions for train influent and effluent concentrations.

Sodium

No significant sodium removal was expected, and none was observed. The largest removals of sodium occurred in the activated sludge unit and carbon column, about 2 percent in both cases based on median concentrations. Increases occurred in the Densator, originating most likely from the coagulants. Although the mean increase was about 9 mg/l, the median increase was only slightly less than 2 mg/l. Because the most frequent and largest increases occurred during August 1972, the problem may be a result of one chemical shipment. The highest observed train effluent concentration was 195 mg/l, approximately 67 percent over the mean.

For practical purposes sodium is completely refractory to the unit processes utilized during this study.

Nickel

Nickel was removed about equally well by both the activated sludge unit

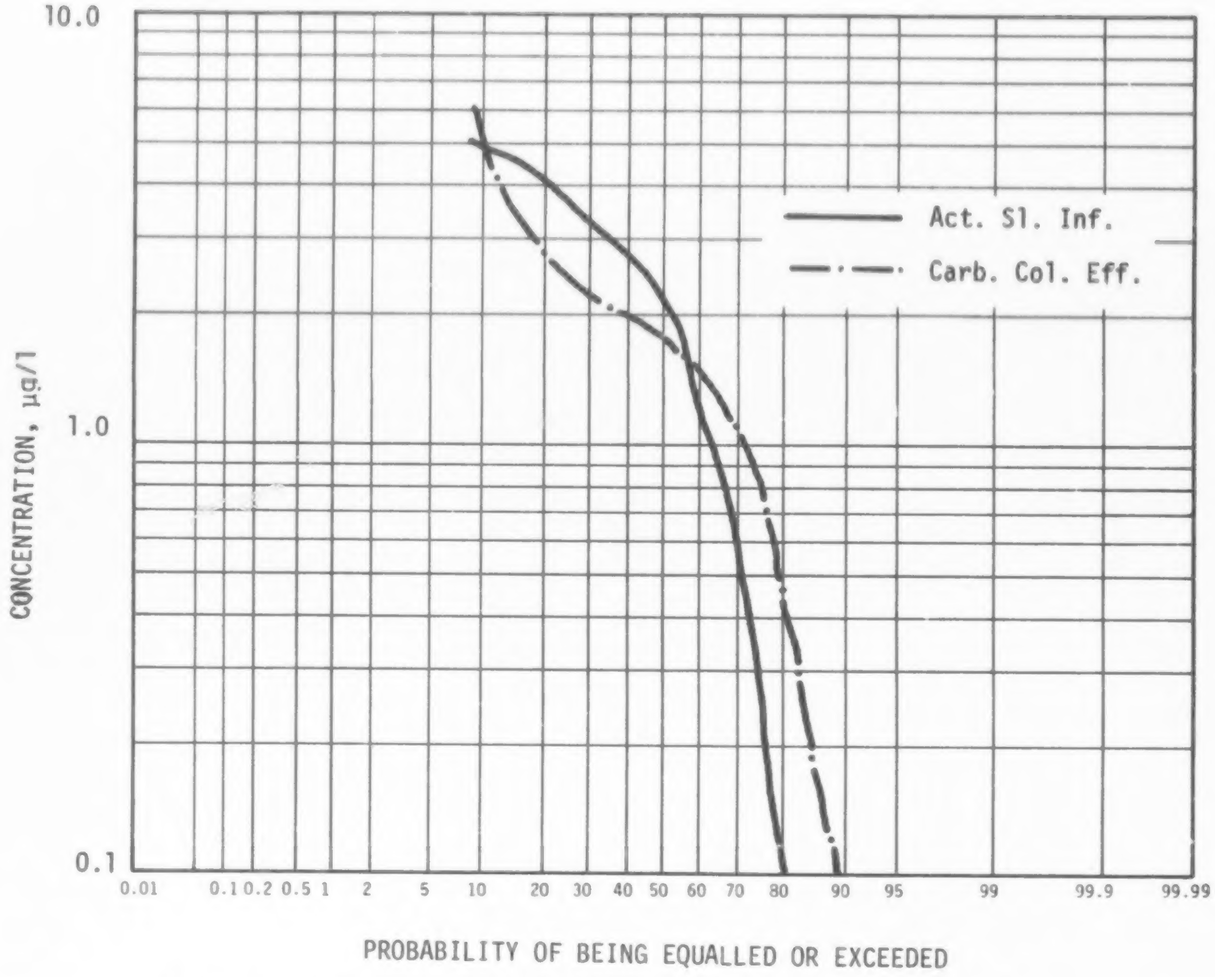

Figure 21. Frequency distributions for molybdenum, high-pH lime coagulation study.

and the Densator. Activated sludge removals were 21 percent (mean) and 18 percent (median), while the Densator removals averaged 36 percent (mean) to 46 percent (median). Reductions through the Densator exhibited a concentration effect (r=0.51), and were inversely proportional to effluent TSS (r=0.44). Percent nickel removals also correlated inversely with TSS, and the concentrations of nickel and TSS exhibited a linear correlation (r=0.52). Further removal of nickel was accomplished by multimedia and carbon filtration, with an observed decrease of about 0.01 mg/l in each unit.

The relatively equal division of nickel removal between the biological process and the AWT process is indicated in Figure 22.

Lead

The largest portion of lead was removed in the activated sludge process, 57 percent (mean) to 70 percent (median), and there were no significant changes in the concentration throughout the remainder of the train. No significant patterns were observed on the multimedia filter, but the carbon column reductions exhibited a concentration effect (r=0.69). The drinking water MCL of 0.05 mg/l was exceeded in 83 percent of the train influent samples and 34 percent of the train effluent samples. The highest train effluent concentration was 0.10 mg/l, which occurred in two samples, both collected during June 1972.

Frequency distributions are shown in Figure 23, and definitely indicate the importance of the biological process for removing lead.

Selenium

The activated sludge unit removed most of the selenium, 83 percent (mean) and 82 percent (median). High-pH lime coagulation removed 21 percent (mean) and 65 percent (median), and the reductions exhibited a concentration effect (r=0.43). Selenium possesses the unusual property of being soluble in caustic alkali solution, which explains the linear correlation between effluent selenium and methyl orange alkalinity (r=0.62). Also, there were negative correlations between the reductions in selenium and methyl orange alkalinity (r=0.33), phenolphethalein alkalinity (r=0.41), and lime dose (r=0.38). Following high-pH lime clarification there was an apparent increase in selenium through the multimedia filters, then a substantial removal on the carbon columns. From the Densator through the carbon columns there was 47 percent removal of selenium (mean), or 71 percent (median) removal. Of all the metals investigated, selenium had the highest average removal efficiency on activated carbon: 51 percent (mean) to 88 percent (median). However, there were no apparent correlations between selenium removal and the operating/process control parameters. The NIPDWR MCL of 0.01 mg/l was exceeded in 52 percent of the train influent samples, and in none of the remaining samples.

Frequency distributions for selected sampling locations are presented in Figure 24.

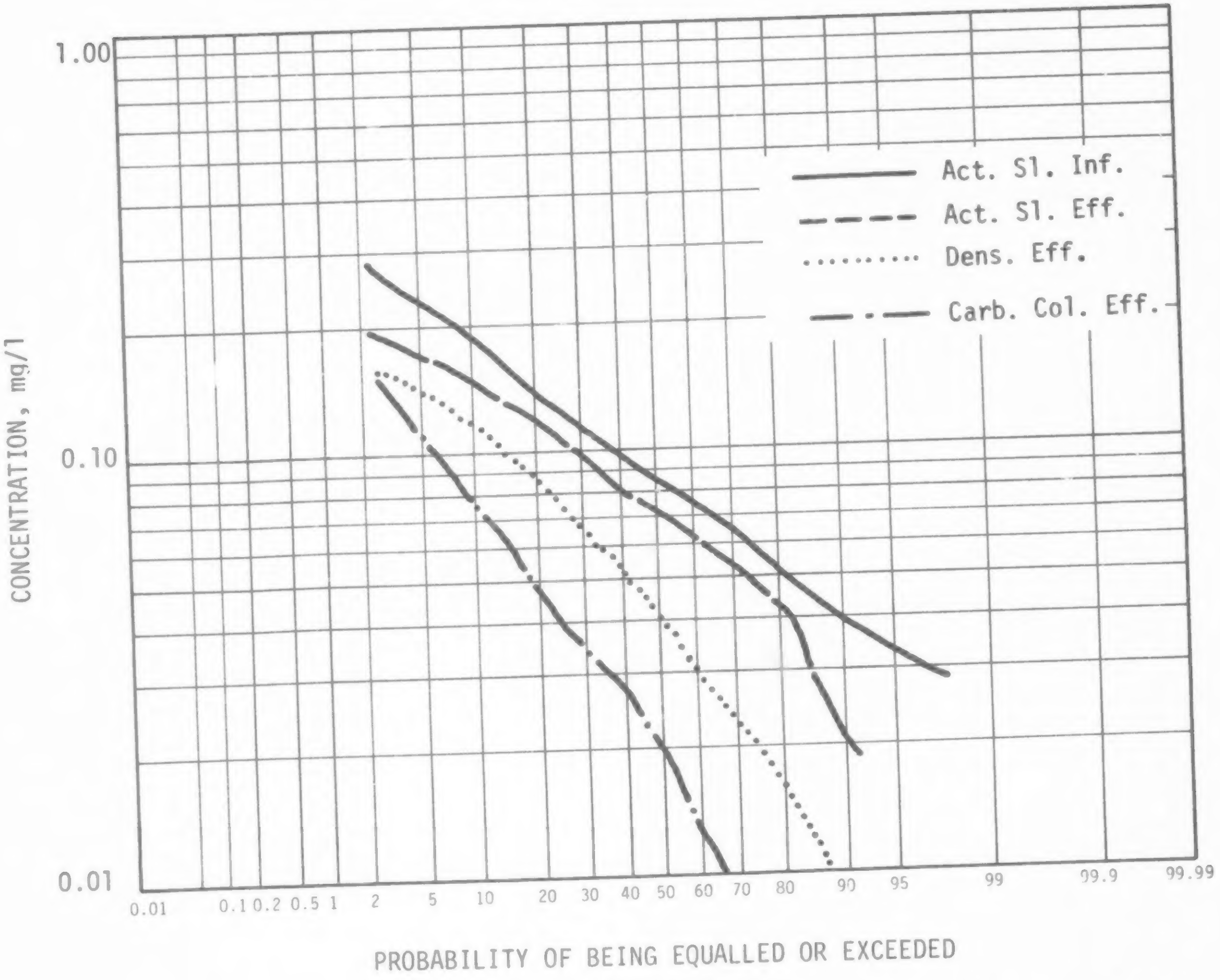

Figure 22. Frequency distributions for nickel, high-pH lime coagulation study.

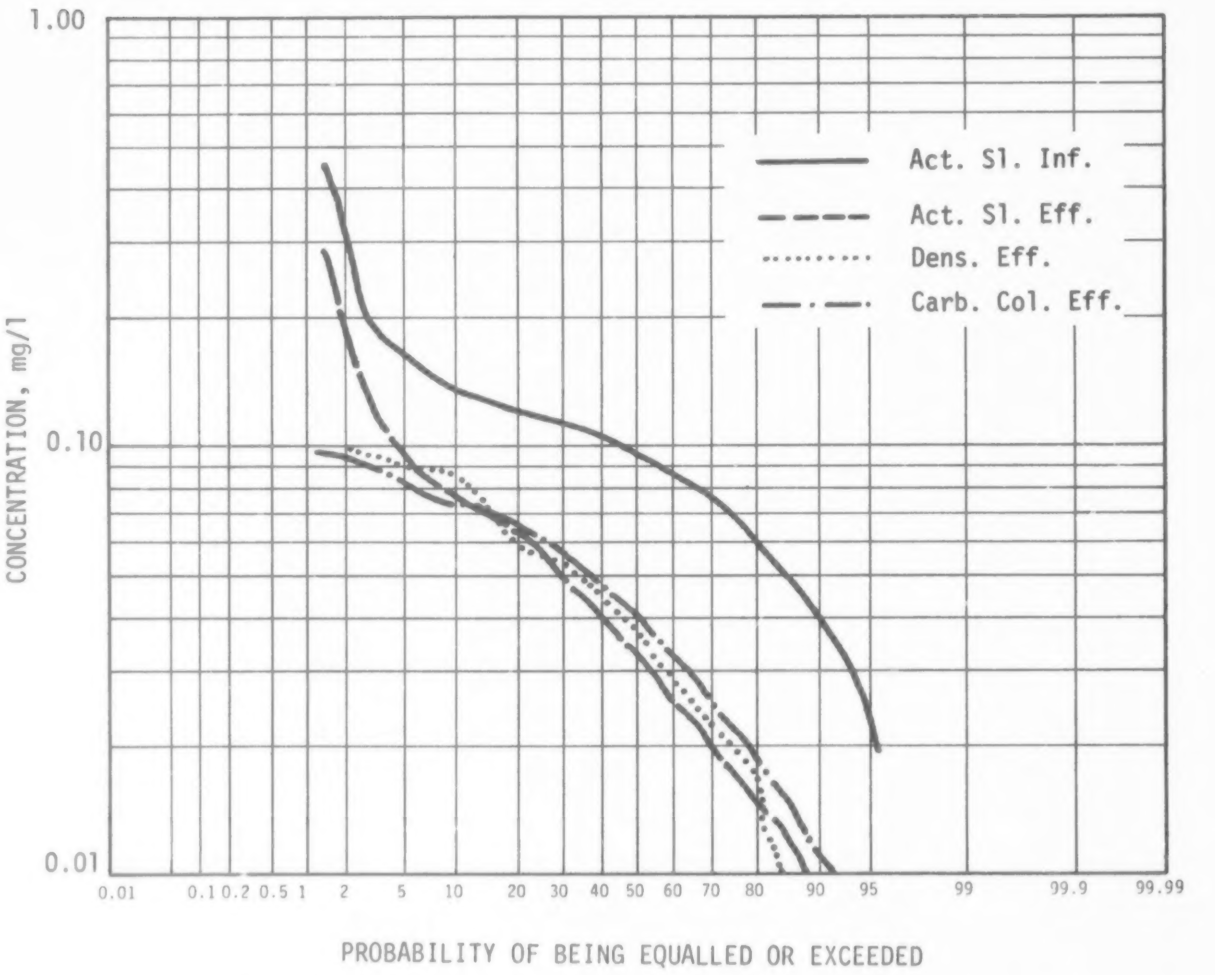

Figure 23. Frequency distributions for lead, high-pH lime coagulation study.

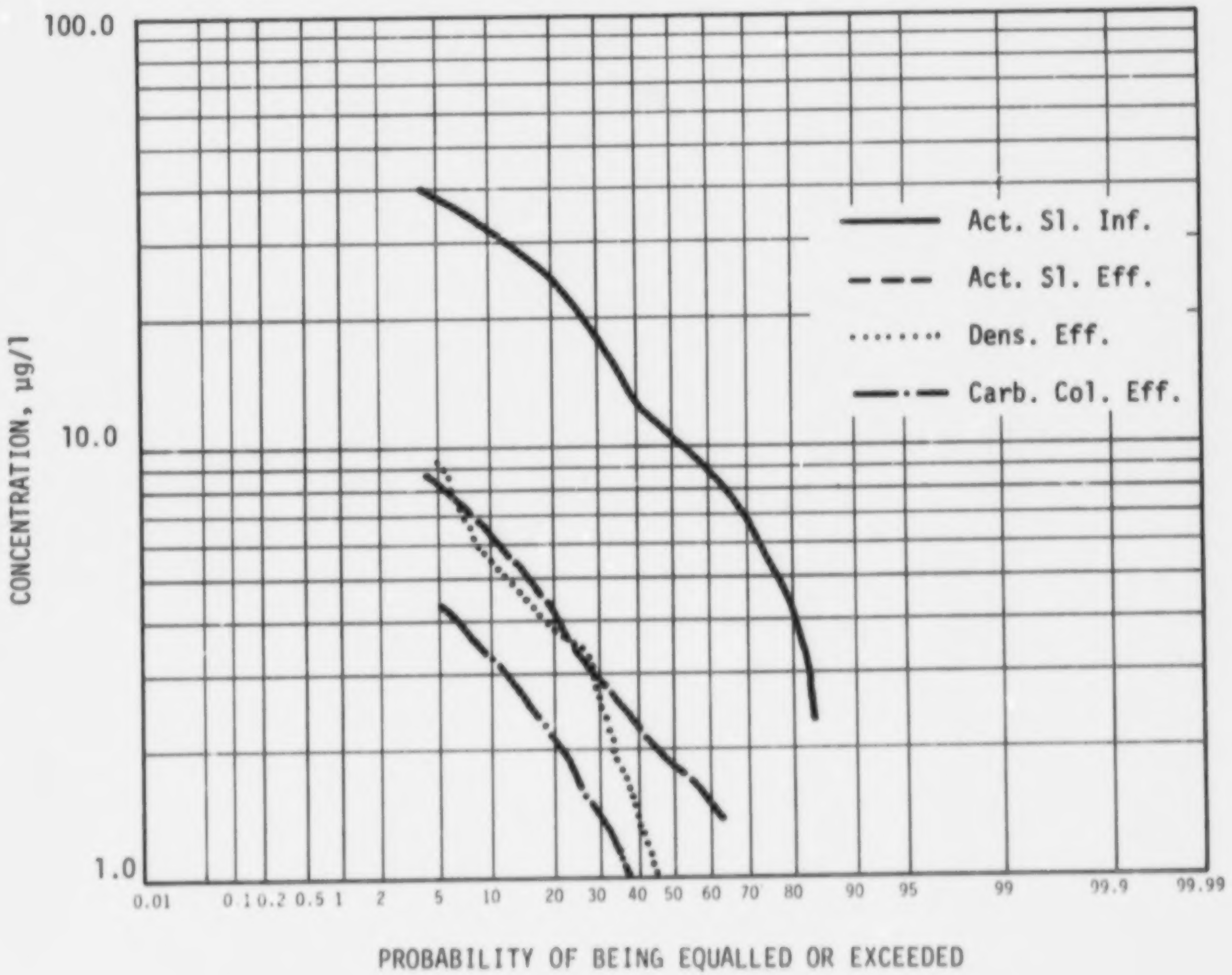

Figure 24. Frequency distributions for selenium, high-pH lime coagulation study.

Silicon

Silicon had negligible removal by the activated sludge process and a slight increase through the Densator and carbon column. All the significant removals occurred in the multimedia filters: 50 percent (mean) and 49 percent (median). Unfortunately, there were insufficient data to develop confidence in the removal efficiencies or correlations with other parameters. The same may be said of strontium and vanadium.

Strontium

The activated sludge process removed some strontium, 11 percent (mean) and 10 percent (median). Little or no removal occurred throughout the remainder of the treatment sequence.

Vanadium

A slight reduction in vanadium occurred in the activated sludge unit, but the multimedia filter exacted the greatest removals: 33 percent (mean) and 26 percent (median). Net mean and median train removals were 37 percent and 18 percent, respectively.

Zinc

Zinc was removed chiefly by biological and chemical treatment, the filter and carbon column only decreasing a few extreme values. Activated sludge removals were 62 percent (mean) and 67 percent (median), while Densator removals averaged 48 percent and 70 percent, respectively.

The Densator reductions exhibited a strong concentration effect (r=0.67), and generally increased as the effluent alkalinities and lime dose increased and as effluent turbidity decreased.

A mean removal of 24 percent was observed across the multimedia filter, although there was no change in the median concentrations. Reductions through the filter were due primarily to a concentration effect (r=0.65), particularly at influent concentrations exceeding about 0.10 mg/l. The same comments apply to the carbon column where a 14 percent removal of mean concentrations occurred without any change in the median values. The highest value of zinc ever observed was 0.88 mg/l in the train influent, well below the Secondary Drinking Water Regulation recommendation of 5.0 mg/l.

SECTION 7

ALUM COAGULATION

GENERAL

The second phase in the investigation of metals removals by AWT processes involved the study of alum coagulation of an activated sludge effluent followed by multimedia filtration and activated carbon adsorption. A 3-week start-up period commenced in early November of 1972 to establish steady-state conditions in the upflow clarifier prior to collecting samples and acquiring data. The starting date, was November 20, 1972, and this phase of the project terminated October 30, 1973 -- nearly a year's duration.

The process configuration utilized at the Demonstration Plant for the alum coagulation phase of the project is shown in Figure 25. The fundamental difference between the three phases of the project was the primary coagulant used for chemical treatment. An average alum dose of 130 mg/l was used to coagulate the activated sludge effluent; however, the low alkalinity in the activated sludge effluent, resulting from nitrification, necessitated the feeding of 50 mg/l lime (as CaO) to permit the coagulation reactions to proceed to completion.

Table 24 summarizes the water quality data for the alum coagulation phase. Effluent quality was excellent, as was the overall performance of the treatment sequence. COD removal was slightly better than 97 percent, and BOD_5 reductions approached 99 percent.

The mean soluble total organic carbon (SOC) concentration in the effluent was 4 mg/l, which was at the lower limit of sensitivity for the analytical instrument being used.

The effluent total dissolved solids (TDS) concentration averaged 491 mg/l, and was not changed significantly by the treatment employed during this phase of the study. No significant changes in either TDS or specific conductance was expected, and none was observed. The treatment sequence proved to be very effective in controlling the suspended solids concentrations in the product water, which averaged only 2 mg/l.

The reductions in microorganism populations observed during the alum coagulation phase were good, but not comparable to the dramatic kills obtained with high-pH lime treatment. The geometric mean fecal coliform density in the effluent from the activated carbon was 630 organisms per

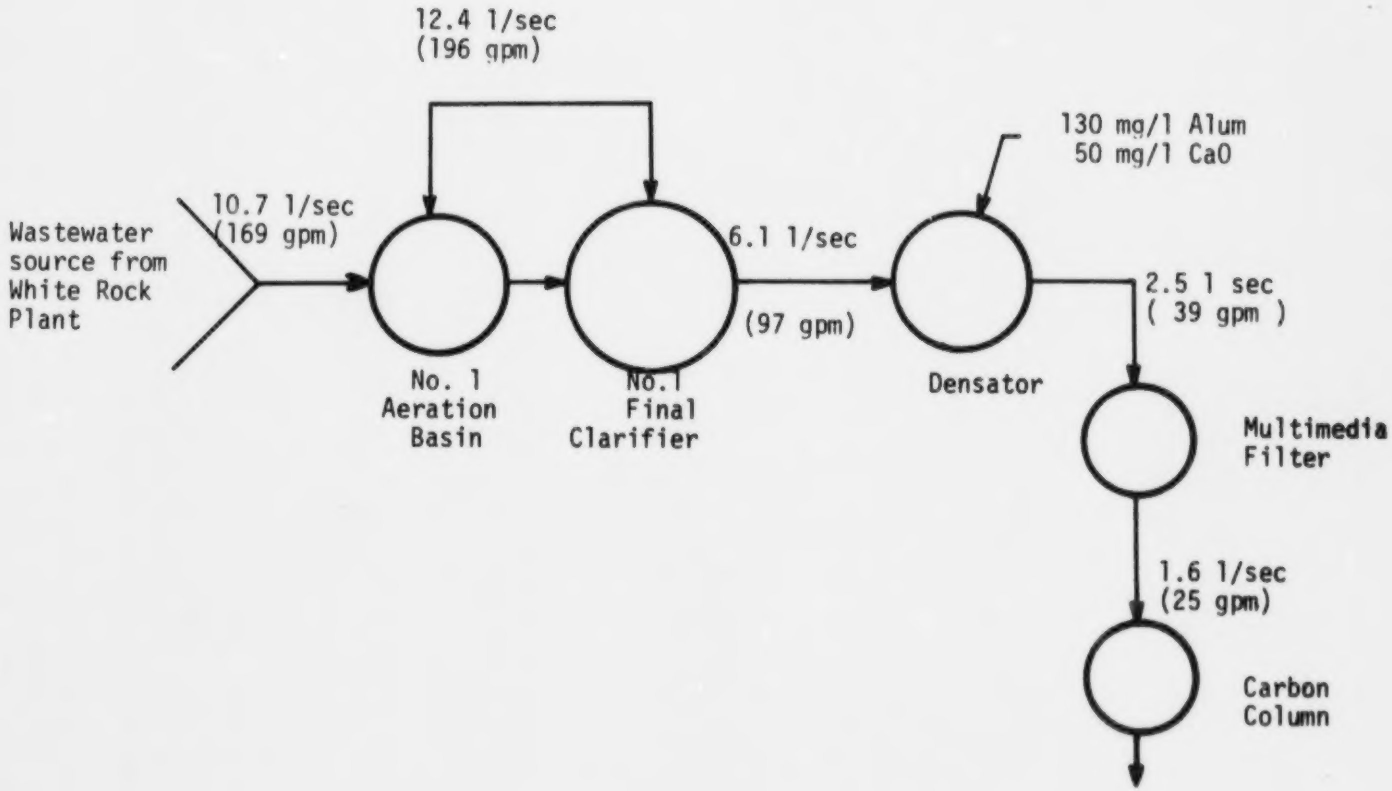

Figure 25. Process configuration: Alum coagulation, November, 1972 - October 30, 1973

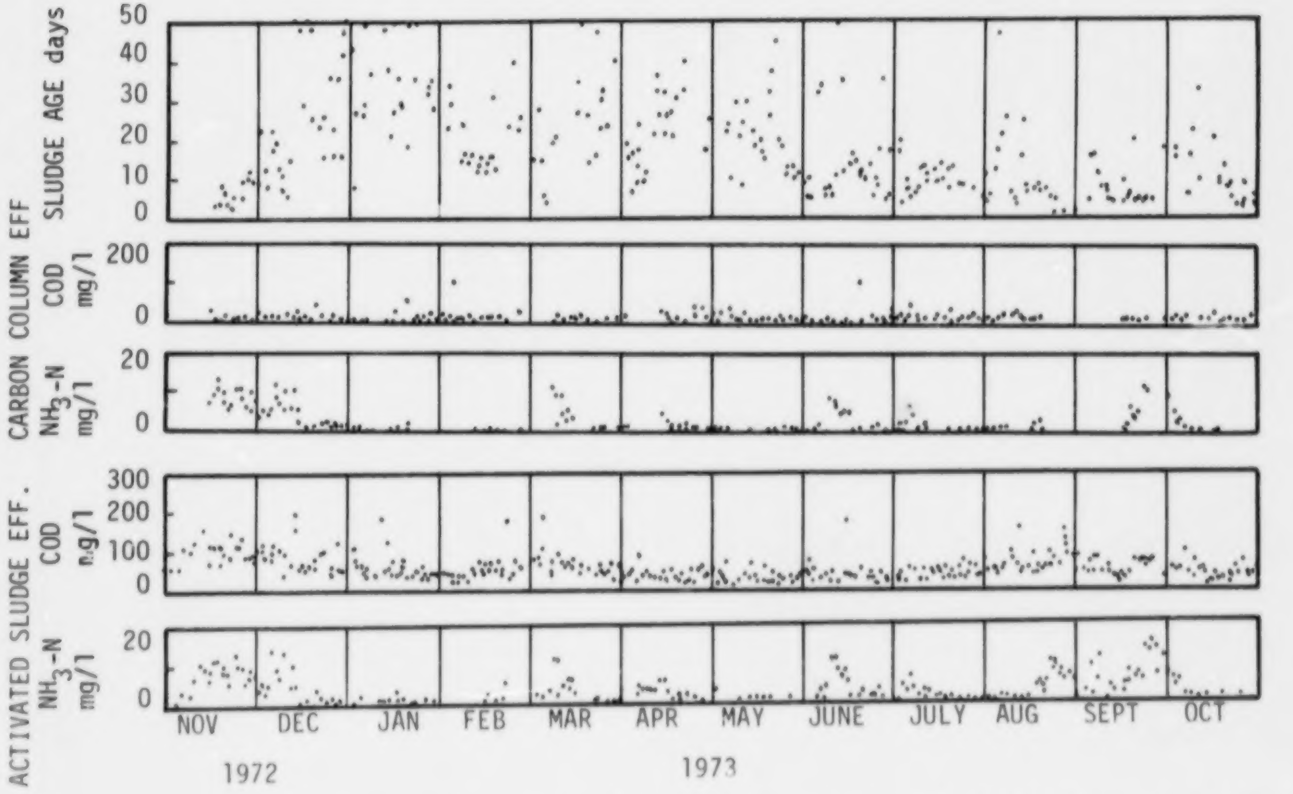

Figure 26. Time series plots of sludge age values, and selected NH_3-N and COD concentrations for the alum coagulation study.

TABLE 24. OVERALL WATER TREATMENT SUMMARY ALUM COAGULATION STUDY

Parameter	Raw Waste-Water mg/l	Carbon Column Effluent mg/l	Reduction (percent)
COD, mg/l	494	13	97.4
SOC, mg/l	--	4	N/A
BOD_5, mg/l	185	<2	>98.9
TSS, mg/l	238	2	99.2
TDS, mg/l	--	491	N/A
SC, µmho/cm	750	711	5.2
NH_3-N, mg/l	16.7	1.7	89.8
Org. N, mg/l	12.4	1.5	87.9
(NO_2+NO_3)-N, mg/l	0.5	8.5	N/A
NO_2-N, mg/l	0.1	0.2	N/A
T-P, mg/l	--	1.9	N/A
pH	7.4	7.5	N/A
T. Alk., mg/l	211	114	46.0
P. Alk., mg/l	0	3	N/A
Standard Plate Count, per ml	--	6.9×10^2	N/A
Total MPN, per 100 ml	--	6.5×10^3	N/A
Fecal MPN, per 100 ml	--	6.3×10^2	N/A

-- Not Available

N/A Not Applicable

100 ml, which is about a four-log reduction.

COMPLETELY-MIXED ACTIVATED SLUDGE

The No. 1 completely-mixed activated sludge system operated during this portion of the research effort with unsettled effluent from the stage I trickling filters at the White Rock STP serving as the influent. Table 25 is a performance and water quality summary for the twelve month study period, and all values presented are arithmetic means. Table 26 is a summary of the hydraulic operation and process control variables for the system.

One objective of this phase was to achieve complete, stable nitrification in the activated sludge system. The effluent NH_3-N concentration averaged 1.7 mg/l, which represented a considerable improvement over the 3.7 mg/l mean for the lime coagulation phase. Figure 26 presents time series plots of the sludge age in the activated sludge process, and effluent concentrations for COD and NH_3-N in both the activated sludge and carbon column effluents.

Operation of the process was not conventional in that the theoretical residence time in the aeration basin was only 4.4 hours (2.05 hours is based on both influent and return sludge flows). The residence time was very low for a nitrifing process when evaluated in terms of conventional design criteria for plug-flow systems. These data indicate that long detention times are not necessary provided that the sludge age is sufficiently high and that adequate oxygen transfer capacity is available. Figure 27 presents the probability distributions for the various forms of nitrogen in the activated sludge influent. Median values are the 50-percentile values, and these data are in rather good agreement with the arithmetic means presented in Table 26. For instance the median concentration for NH_3-N during this phase was 13.2 mg/l, while the mean concentration was 13.8 mg/l. The close agreement between mean and median, and the fact that the data plot as relatively straight lines on log-probability paper indicates that the data closely approximate a normal distribution.

Figure 28 presents frequency distributions for the upflow clarifier effluent nitrogen concentrations, and these data closely approximate the nitrogen concentrations expected in the activated sludge effluent, with the obvious exception of the organic nitrogen data. The median NH_3-N concentration shown is 0.6 mg/l, although the mean concentration in the upflow clarifier effluent was 2.04 mg/l. The 240 percent discrepancy between mean and median values is not uncommon when evaluating water quality data for AWT processes.

Figure 29 presents the probability distribution for COD and TOC concentrations observed in the activated sludge influent. These values resulted in food to microbe ratios of 0.311 kg COD/day/kg MLSS and 0.081 kg soluble TOC/day/kg MLSS, respectively.

TABLE 25. PERFORMANCE SUMMARY OF THE COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM, ALUM COAGULATION STUDY

Parameter	Raw Waste-Water	Activated Sludge Influent (mg/l)	Activated Sludge Effluent (mg/l)	Reduction by the A.S. System only (percent)
COD	494	237	57	75.95
TOC, Soluble	--	20	10	50.00
BOD_5	185	62	28	54.84
TSS	238	142	28	80.28
TDS	657	507	498	1.78
SC, μmho/cm	--	750	691	7.87
NH_3-N	16.7	13.82	2.36	82.92
Org. N	12.4	10.06	3.85	61.73
NO_2+NO_3-N	--	1.2	8.4	N/A
NO_2-N	--	0.126	0.076	39.68
Total P	--	9.8	7.8	20.41
pH, units	7.4	7.3	7.2	N/A
T. Alk. (as $CaCO_3$)		206	126	N/A
P.Alk. (as $CaCO_3$)		0	0	38.8
Standard Plate Count, per ml	--	1.3×10^6	5.1×10^4	N/A
Total Coliforms per 100 ml	--	1.3×10^7	4.2×10^5	N/A
Fecal Coliforms per 100 ml	--	1.8×10^6	3.1×10^4	N/A

-- Not Available
N/A Not Applicable

TABLE 26. PROCESS CONTROL SUMMARY FOR THE COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM, ALUM COAGULATION STUDY

HYDRAULIC OPERATION	
Q (influent)	10.7 l/sec (169 gpm)
Q (return)	10.7 l/sec (169 gpm)
Q (waste)	4994 l/day (1293 gpd)
Aeration T	2.05 hours
Clarifier Overflow Rate	14.0 m^3/day-m^2 (344 gal/$ft.^2$-day)
Weir loading	33.2 m^3/m-day (2674 gal/ft-day)
PROCESS CONTROLS	
MLSS	4127 mg/l
MLVSS	2852 mg/l
RAS	8248 mg/l
SVI	182 mg/l
Air supplied	154.8 l/sec (328 cfm)
D.O.	2.6 mg/l
D.O. Uptake rate	60.6 mg/l-hr.
F/M (COD)	0.311 day^{-1}
F/M (SOC)	0.026 day^{-1}
F/M (BOD)	0.081 day^{-1}
Sludge Age	10.6 days
Temperature	21°C (70°F)

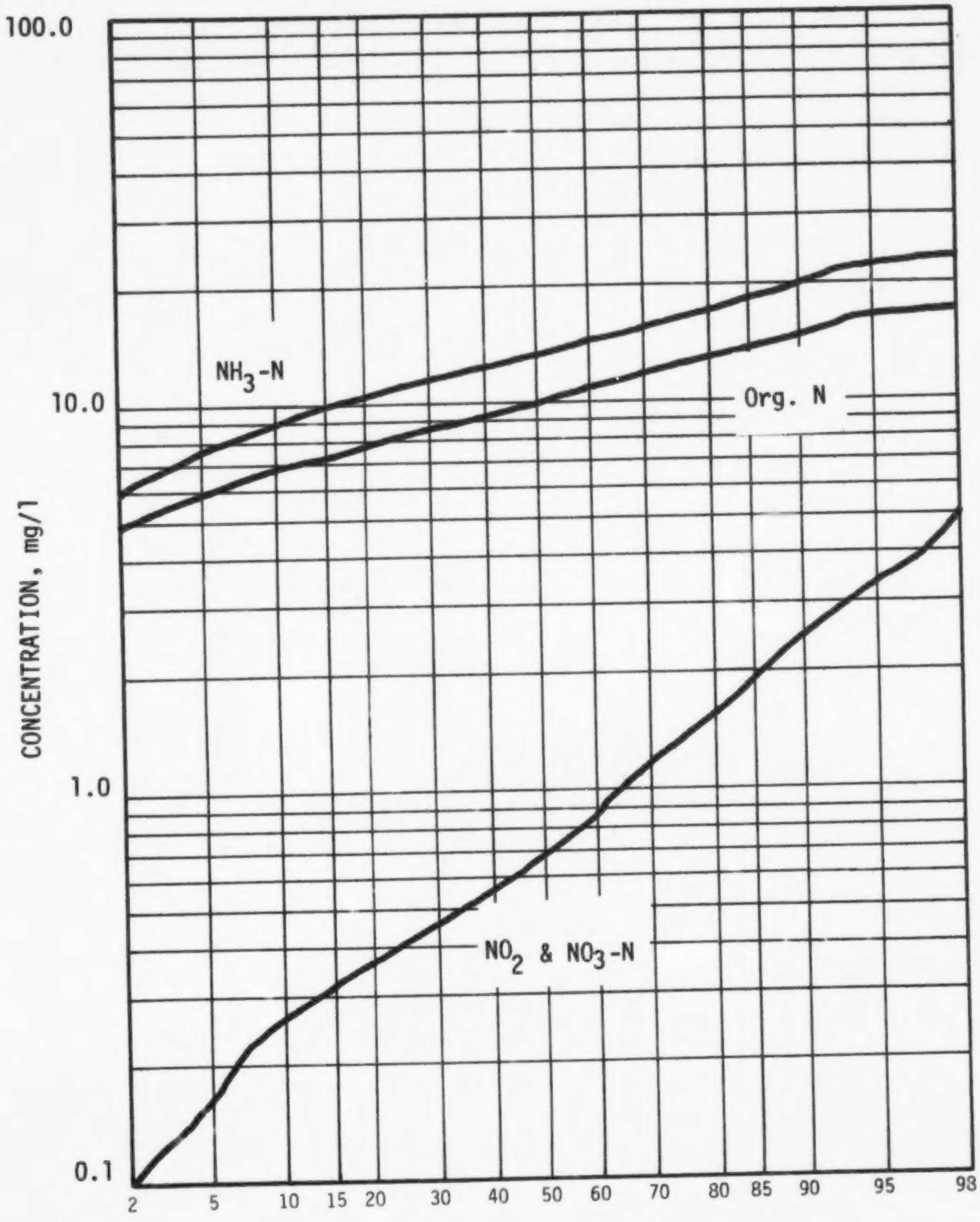

Figure 27. Probability distributions for different forms of nitrogen in the activated sludge influent.

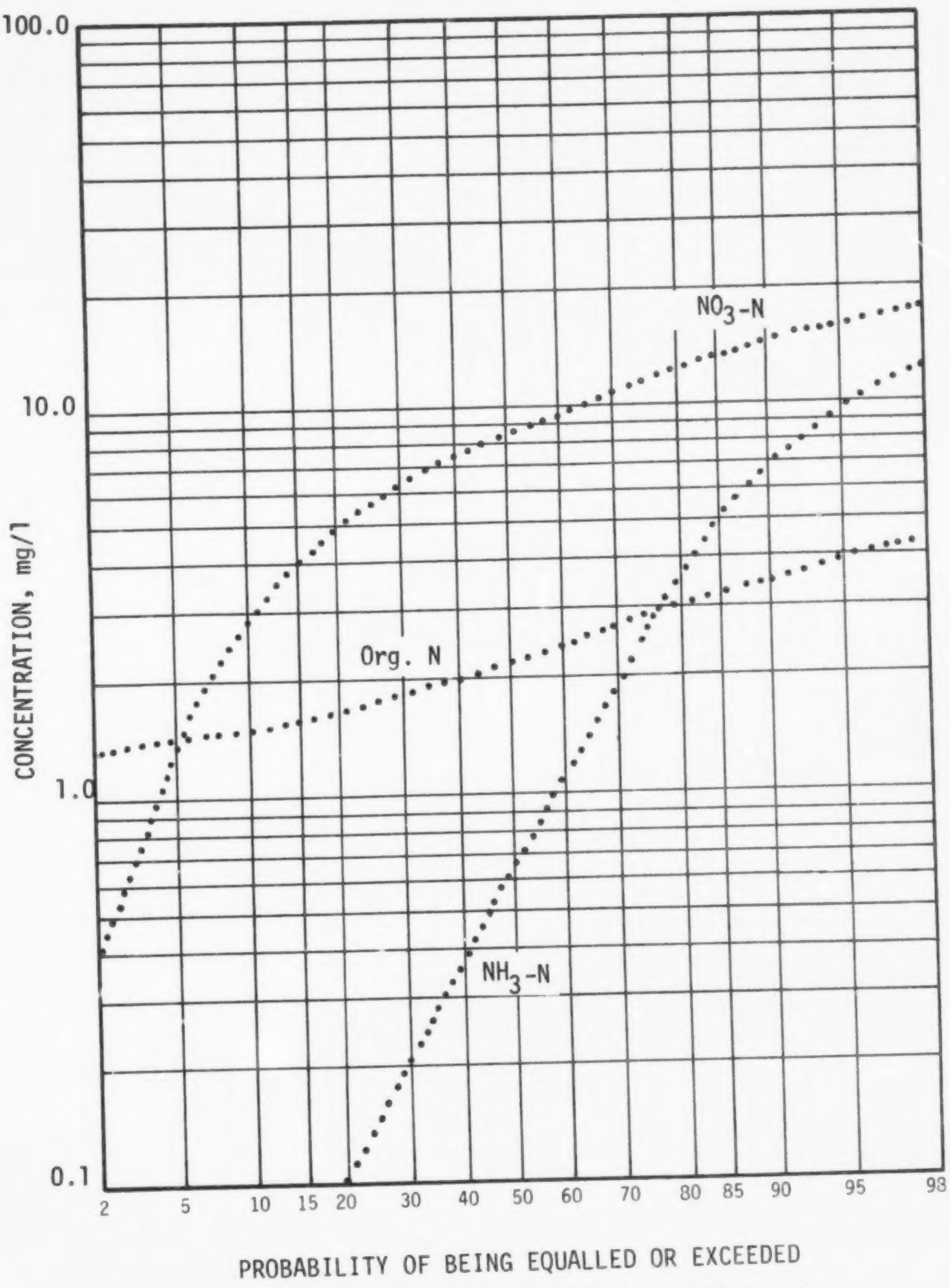

Figure 28. Probability distributions for different forms of nitrogen in the upflow clarifier effluent.

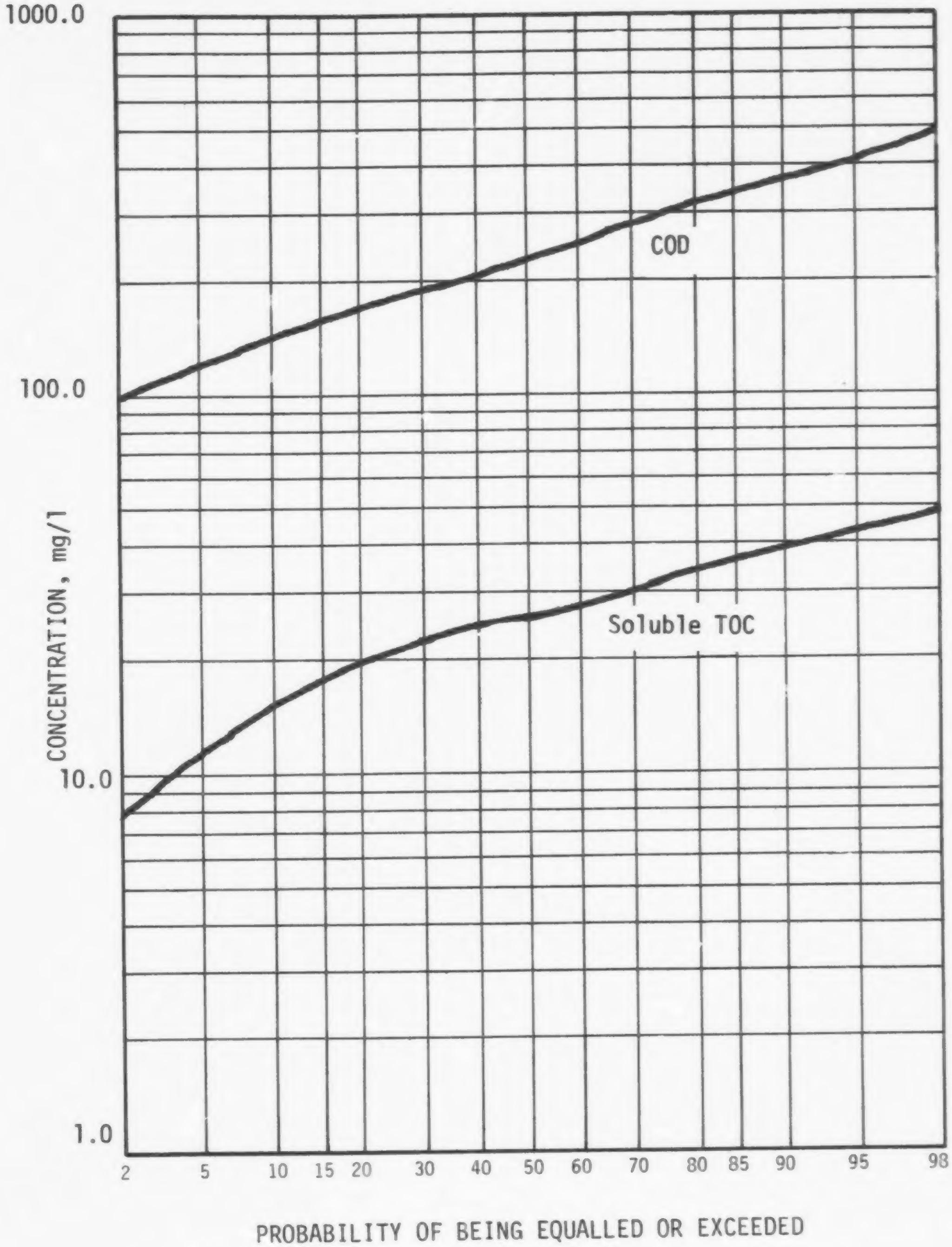

Figure 29. Probability distributions for COD and TOC concentrations in the activated sludge influent.

UPFLOW CLARIFIER

The performance of the upflow clarifier (Infilco Densator) is summarized in Table 27. The chemical treatment process performed reasonably well, and the process control criteria are summarized in Table 28.

The operation of the Densator was relatively conventional with the exception of a few significant points. The mean value of the dissipation function, G, was 67 sec^{-1} during this portion of the study, which is substantially lower than the 500 to 1000 sec^{-1} normally found in mixing basins. However due to the construction of the Densator, the theoretical residence time in mixing zone was 8.4 minutes, about 11 times the normal detention time of 45 seconds. The resulting Gt value of 34,000 is reasonable for mixing basins.

The average recycle flow of 0.3 liter/sec (4gpm) is somewhat misleading. Sludge was recycled during portions of the study, but no improvement in effluent quality was observed as a function of the sludge recycle; therefore, during most of the alum coagulation phase sludge recycle was not employed.

Figure 29a shows the observed frequency distributions for total phosphorus and turbidity values. The median total phosphorus concentration was 2.3 mg/l, which is much higher than one would expect from an AWT facility, but the average alum dose of 130 mg/l would be expected to yield about that concentration. Factually, budgetary constraints prohibited feeding alum doses adequate for acceptable phosphorus removal.

The reduced alum dose probably had a detrimental effect on metals removals, but the extent of the effect of reduced coagulant dose cannot be accurately assessed. It should be noted that the turbidity data indicate that excellent coagulation and liquid/solids separation were obtained during this part of the project.

MULTIMEDIA FILTERS

The No. 1 mixed-media filter was in operation during most of this phase of the project, although the No. 2 dual-media filter was occasionally used. The filters were operated at an average flow of 2.5 liters/sec. (39 gpm) which resulted in a mean filtration rate of 7.58 m/hr. (3.1 gpm/sq.ft.). The filters were backwashed when the headloss was 9 to 10 feet. The average run time between filter washes was 40 hours, and the backwash water consumption was 2.31 percent of the product water.

The data in Table 29 indicate that the filters performed well. The reduction in suspended solids was almost 60 percent, and the product water clarity was always very good. No statistically significant changes in the various forms of nitrogen were observed. The microbiological data indicate that the filters were not very effective in reducing the bacterial populations; all reductions were less than one-half log.

TABLE 27. PERFORMANCE SUMMARY FOR THE UPFLOW CLARIFIER, ALUM COAGULATION STUDY

Parameter	Activated Sludge Effluent mg/l	Densator Effluent mg/l	Reduction (percent)
COD	57	28	50.9
TOC, Soluble	10	8	20.0
BOD_5	28	6	78.6
TSS	28	17	39.3
TDS	498	532	N/A
SC, µmho/cm	691	723	N/A
NH_3-N	2.4	2.0	13.6
Org. N	3.9	2.4	37.9
NO_2+NO_3-N	8.4	8.6	N/A
NO_2-N	0.08	0.10	N/A
Total P	7.8	3.0	61.5
pH, units	7.2	7.6	N/A
T. Alk as $CaCO_3$	126	120	4.8
P. Alk as $CaCO_3$	0	5	N/A
Standard Plate Count per ml	$5.1x10^4$	$4.0x10^3$	92.2
Total Coliforms per 100 ml	$4.2x10^5$	$2.3x10^4$	94.5
Fecal Coliforms per 100 ml	$3.1x10^4$	$1.8x10^3$	94.2

N/A: Not Applicable

TABLE 28. PROCESS SUMMARY FOR THE UPFLOW CLARIFIER, ALUM COAGULATION STUDY

Q (influent)	6.1 l/sec (97 gpm)
Q (recycle)	0.3 l/sec (4 gpm)
Q (waste)	75064 l/day (19,832 gpd)
Mixing T	8.4 minutes
G	67 sec.^{-1}
Flocculation T	48 minutes
G	80 sec.^{-1}
Settling T	4.3 hours
Clarifier overflow rate	28.2 $m^3/\text{day-}m^2$ (691 $\text{gal/ft}^2\text{-day}$)
Weir loading	31.6 $m^3/\text{m-day}$ (2540 gal/ft-day)
Alum Dose	130 mg/l
Lime Dose	50 mg/l

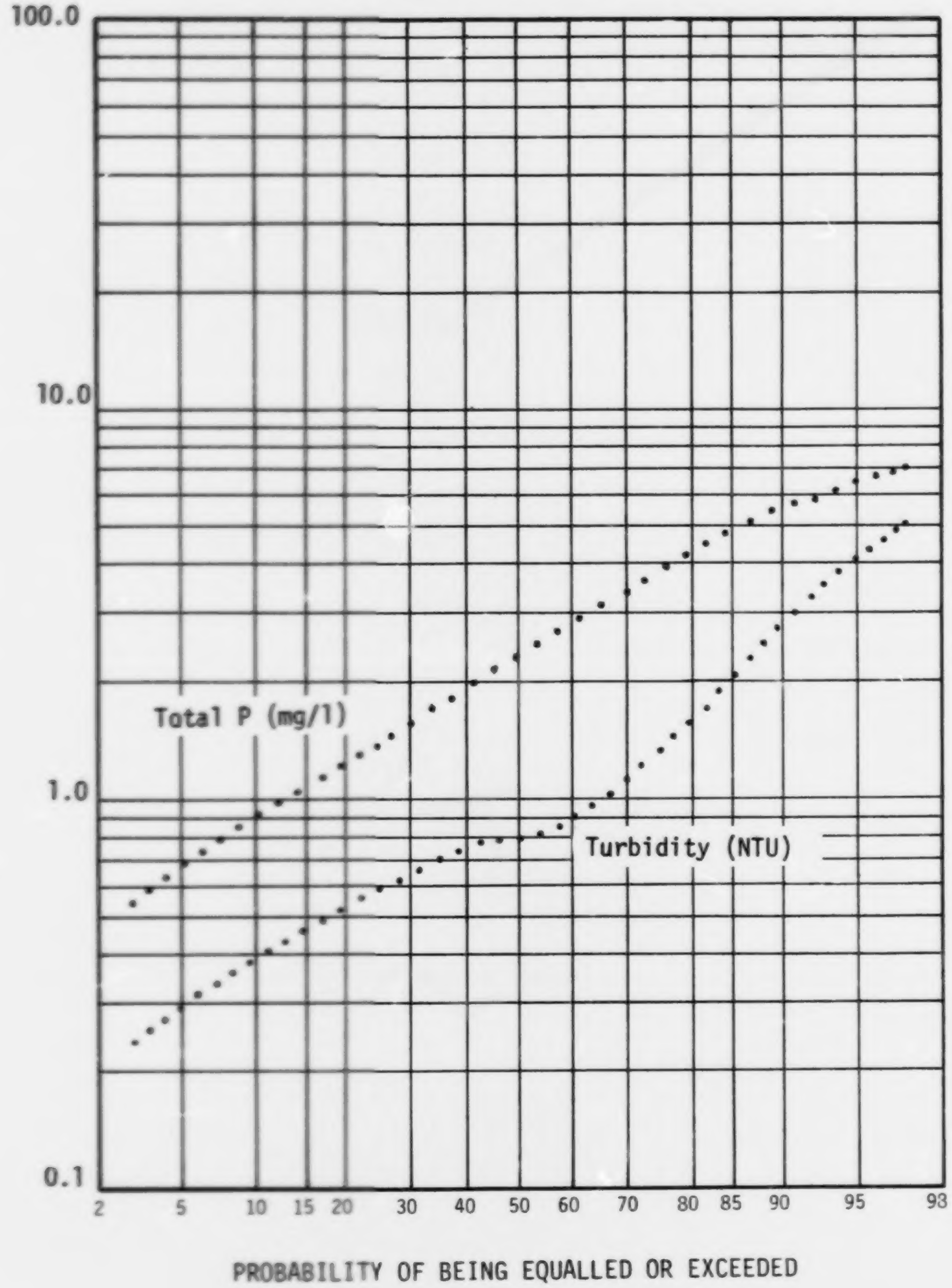

Figure 29a. Frequency distributions for total P and turbidity values in the upflow clarifier effluent.

TABLE 29. PERFORMANCE SUMMARY FOR THE MULTIMEDIA FILTER, ALUM COAGULATION STUDY

Parameter	Densator Effluent (mg/l)	Multimedia Filter Effluent (mg/l)	Reduction (percent)
COD	28	26	71
TOC, Soluble	8	8	0.0
BOD_5	6	3	50.0
TSS	17	7	58.8
TDS	532	515	3.2
SC, μmho/cm	723	710	1.8
NH_3-N	2.0	2.1	2.0*
Org. N	2.4	2.1	12.1
NO_2+NO_3-N	8.6	8.6	0.0
NO_2-N	0.10	0.15	42.3*
Total P	3.0	2.4	20.0
pH, units	7.6	7.5	N/A
T. Alk as $CaCO_3$	120	117	2.5
P. Alk as $CaCO_3$	5	4	20.0
Standard Plate Count per ml	$4.0x10^3$	$2.6x10^3$	35.0
Total Coliforms per 100 ml	$2.3x10^4$	$1.3x10^4$	43.5
Fecal Coliforms per 100 ml	$1.8x10^3$	$1.5x10^3$	16.7

ACTIVATED CARBON ADSORPTION COLUMN

The No. 3 column was placed in service with a fresh charge of virgin carbon in November 1972. During portions of the months of February and March 1973, the No. 4 column replaced the No. 3 column in the treatment sequence; however, from March until the end of the alum coagulation study the No. 3 column was used in the treatment sequence. The final X/M was 0.29 lb. COD applied/lb. carbon, although the COD removal efficiency had not begun to decline noticeably.

The carbon contactors were operated at an average flow of 1.6 liters/sec (25 gpm) which resulted in a surface loading of 4.80 m/hr. (2.0 gpm/sq.ft.) and an empty-bed contact time of 37 minutes. The average run time between backwashes was 113 hours, and the backwash water consumption averaged 0.85 percent of the product water.

Performance in the column was excellent, as the data in Table 30 indicate. COD reduction averaged 50 percent, as did the soluble TOC concentration (SOC). At a surface loading of 4.89 m/hr. (2.0 gpm/ft.^{2}), the column functioned as an excellent filter and reduced the TSS concentration by 71 percent to 2 mg/l.

Frequency distributions for the observed concentrations of different forms of nitrogen are shown in Figure 30. The median ammonia nitrogen concentration of 0.4 mg/l indicates that good nitrification was obtained during this portion of the project. The median nitrate and organic nitrogen concentrations were 8.2 and 1.4 mg/l, respectively.

Figure 31 presents frequency distributions for COD, TOC, color, and TSS values in the carbon column effluent. The product water COD concentrations were relatively low and had a median concentration of less than 12 mg/l. The COD concentration was less than 20 mg/l in 85 percent of the samples analyzed. The curve for TSS data indicates that the down-flow carbon columns provided additional filtering, and that 95 percent of the samples had TSS concentrations less than 10 mg/l.

The carbon adsorption columns were not particularly effective in reducing the population of microorganisms. In general a half-log reduction was observed through the carbon column.

TABLE 30. PERFORMANCE SUMMARY FOR THE ACTIVATED CARBON ADSORPTION COLUMN, ALUM COAGULATION STUDY

Parameter	Multimedia Filter Effluent (mg/1)	Carbon Column Effluent (mg/1)	Reduction (percent)
COD	26	13	50.0
TOC soluble	8	4	50.0
BOD_5	3	<2	<33.3
TSS	7	2	71.4
TDS	515	491	4.7
SC, μmho/cm	710	711	N/A
NH_3- N	2.08	1.71	17.8
Org. N	2.10	1.49	22.0
NO_2+NO_3-N	8.6	8.5	1.2
NO_2-N	.15	0.22	N/A
Total P	2.4	1.9	20.8
pH, units	7.5	7.5	N/A
T. Alk. as $CaCO_3$	117	114	2.6
P.Alk. as $CaCO_3$	4	3	25.0
Std. Plate Count per ml	2.6×10^3	6.9×10^2	73.5
Total Coliforms per 100 ml	1.3×10^4	6.5×10^3	50.0
Fecal Coliforms per 100 ml	1.5×10^3	6.3×10^2	58.0

N/A: Not Applicable

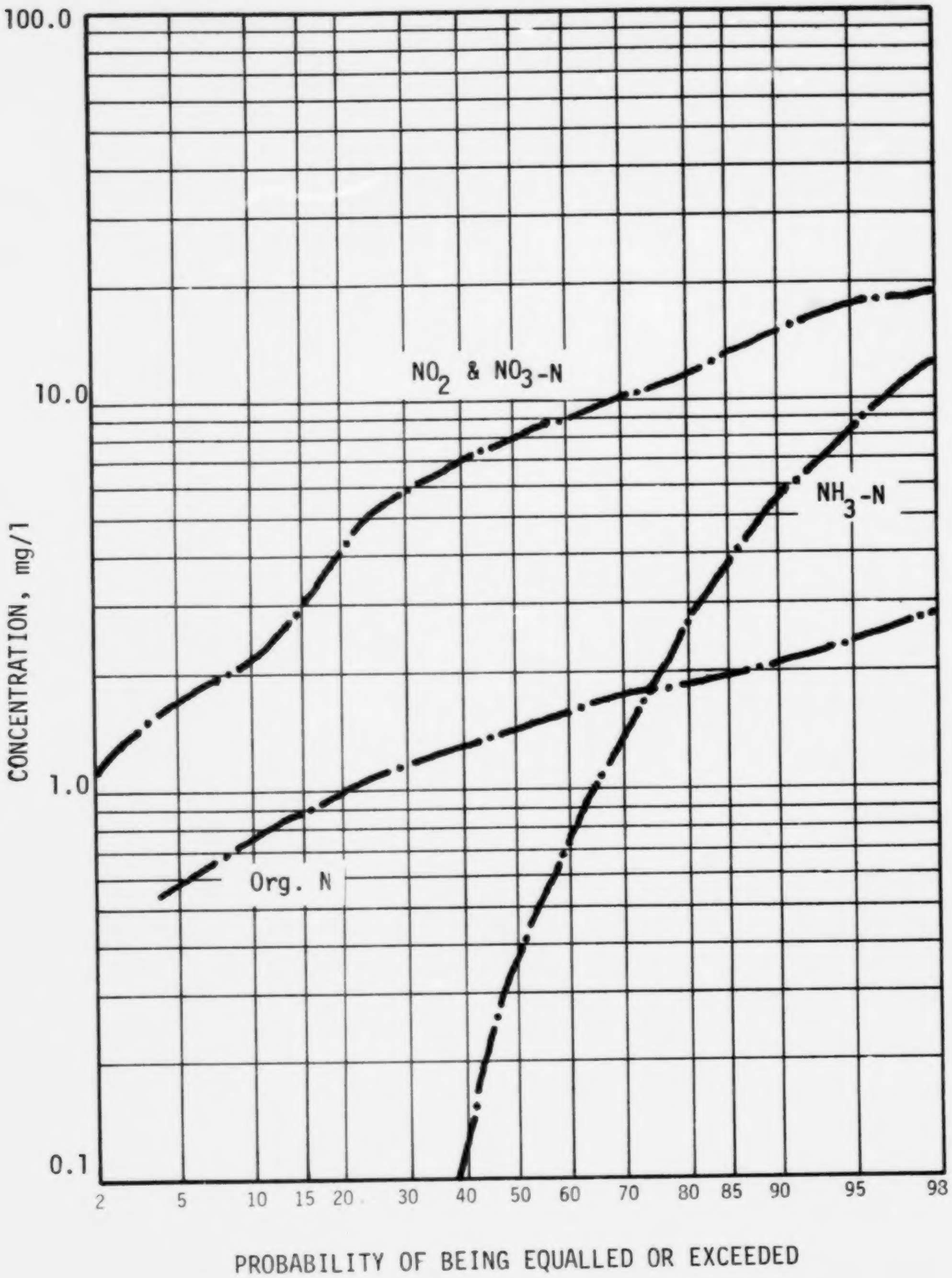

Figure 30. Frequency distributions for observed nitrogen concentrations in the final product water, alum coagulation study.

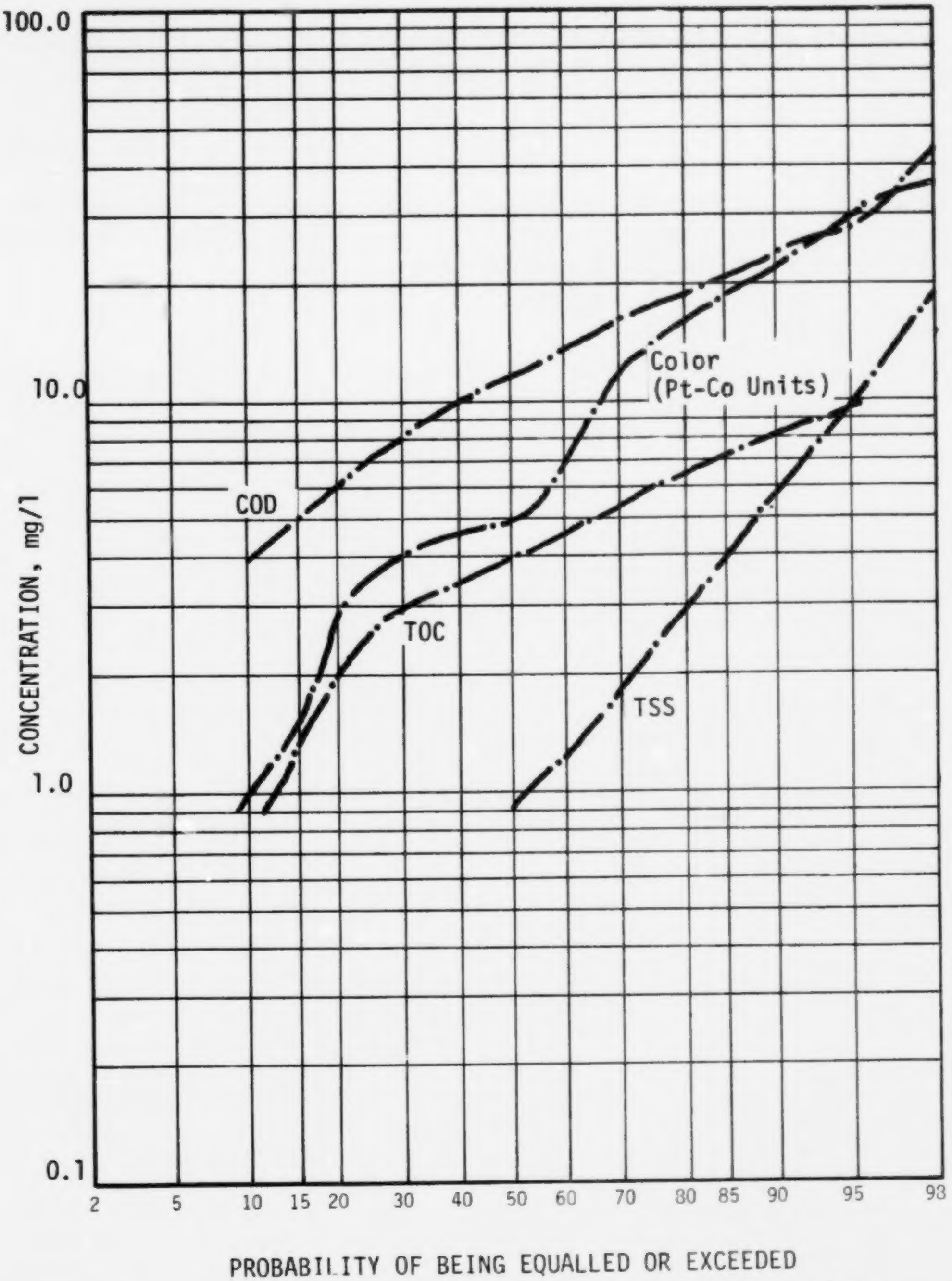

Figure 31. Frequency distributions for selected water quality parameters in the final product water, alum coagulation study.

METALS REMOVALS

A summary of the metals data obtained during the alum coagulation study appears in Tables 31 through 35, in the order of treatment sequence.

Silver

All samples analyzed during November and December had less than the observable detection limit of 1.0 μg/l Ag; therefore , analysis for silver was terminated after the first week of January 1973.

Aluminum

Analysis for aluminum was initiated on April 1, 1973, because of the interest in aluminum addition originating from the alum. A relatively large removal occurred through the activated sludge process, 34 percent and 61 percent of the mean and median concentrations, respectively. In the up-flow clarifier, the mean concentration increased 1.7 mg/l, and the median concentration increased 0.8 mg/l. These represent about 14 percent and 7 percent, respectively, of the amount of aluminum fed (11.8 mg/l as aluminum). Both the influent and effluent probability distributions exhibited parallel, log-normal patterns, indicating the increase was consistent yet also dependent upon the influent concentration. The effluent concentration was proportional to the alum dose (r=0.40), but correlation is poor. It appears that the higher pH values resulting from the use of lime was a dominant factor in increasing the solubility of aluminum, as effluent aluminum was linearly proportional to phenolphthalein alkalinity (r=0.78).

The highest removals of aluminum within the treatment train occurred in the multimedia filter, both the mean and median removals being about 64 percent. Filter reductions exhibited a concentration effect (r=0.94), and were inversely proportional to effluent TSS and turbidity. The effluent concentration of aluminum was also proportional to TSS (r=0.77) and turbidity (r=0.51).

Further removals occurred in the carbon column, 23 percent and 65 percent based on mean and median values. Reductions were again proportional to the influent concentration (r=0.59). Removal of aluminum in both the multimedia filter and carbon column was nearly sufficient to offset the increase in the Densator. Although the mean train effluent concentration exceeded the mean activated sludge effluent concentration, there was an overall train of removal of aluminum amounting to 5 percent (mean) or 78 percent (median). The large difference between these removal efficiencies arises from the extreme concentrations imparted by the alum coagulation. Consequently, the frequency of extreme values was roughly the same in the Densator, filter, and carbon column effluents.

Arsenic

Arsenic was removed by each unit process in the treatment train. Mean and median removals were 12 percent and 6 percent through the activated

TABLE 31. ACTIVATED SLUDGE INFLUENT METALS SUMMARY ALUM TREATMENT NOVEMBER 1972 - OCTOBER 1973

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.0	0.0	0.0	0.0	0.0	9
Al	0.60	0.55	0.63	0.32	1.80	0.18	50
As*	8.5	8.4	11.4	12.6	100.0	0.0	87
B	0.36	0.35	0.36	0.071	0.54	0.19	84
Ba	0.125	0.116	0.132	0.072	0.48	0.03	74
Be*	0.010	0.007	0.014	0.013	0.040	0.0	23
Ca	56.0	57.7	59.3	14.4	105.0	31.0	65
Cd	11.0	11.0	12.2	6.1	34.0	1.0	104
Co	0.024	0.025	0.029	0.015	0.080	0.0	90
Cr	0.215	0.191	0.236	0.146	0.750	0.027	104
Cu	0.30	0.22	0.33	0.25	1.03	0.01	65
Fe	1.17	1.13	1.28	0.93	7.80	0.28	65
Hg*	0.36	0.36	0.52	0.59	3.20	0.0	50
K	12.8	13.2	13.3	1.7	16.7	11.8	9
Mg	4.78	4.77	4.80	0.60	6.52	3.67	23
Mn	0.080	0.082	0.083	0.016	0.130	0.054	66
Mo*	13.0	9.3	20.9	34.4	170.0	0.0	26
Na	90.5	90.5	92.0	16.5	123.0	55.0	52
Ni	0.100	0.101	0.114	0.064	0.38	0.01	66
Pb	0.110	0.109	0.121	0.053	0.35	0.03	103
Se*	3.0	3.3	4.6	4.6	19.5	0.0	66
Si	9.8	10.1	10.3	2.4	14.5	7.0	12
V*	5.2	4.7	4.8	1.2	7.2	2.1	17
Zn	0.320	0.364	0.520	0.66	4.10	0.05	66

Concentration in mg/l
* μg/l

TABLE 32. ACTIVATED SLUDGE EFFLUENT METALS SUMMARY ALUM TREATMENT NOVEMBER 1972 - OCTOBER 1973

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.0	0.0	0.0	0.0	0.0	9
Al	0.24	0.29	0.42	0.46	2.20	0.09	50
As*	8.0	8.1	10.1	8.0	44.5	1.8	90
B	0.35	0.35	0.35	0.067	0.60	0.17	85
Ba	0.050	0.065	0.065	0.051	0.36	0.01	74
Be*	0.0	0.003	0.005	0.008	0.03	0.0	23
Ca	52.0	53.6	55.8	16.4	105.0	27.1	65
Cd*	5.0	5.0	5.6	2.3	11.0	0.0	104
Co	0.020	0.022	0.026	0.017	0.08	0.0	90
Cr	0.060	0.054	0.066	0.042	0.27	0.006	104
Cu	0.050	0.05	0.054	0.020	0.113	0.012	65
Fe	0.32	0.30	0.33	0.13	0.80	0.09	65
Hg*	0.15	0.18	0.26	0.36	2.2	0.0	49
K	12.4	12.6	12.7	1.1	14.8	11.2	9
Mg	4.55	4.64	4.67	0.53	6.20	3.92	23
Mn	0.053	0.050	0.055	0.020	0.110	0.013	66
Mo*	2.7	2.6	4.2	4.3	15.4	0.0	27
Na	87.0	87.7	89.2	16.7	125.0	50.0	52
Ni	0.070	0.073	0.079	0.038	0.28	0.02	66
Pb	0.04	0.046	0.054	0.032	0.17	0.01	104
Se*	0.5	1.2	1.1	1.6	7.5	0.0	68
Si	10.2	9.4	9.7	2.2	12.3	5.6	12
V*	4.4	4.0	4.2	1.2	6.2	1.4	18
Zn	0.120	0.135	0.156	1.56	1.06	0.04	66

Concentration in mg/l
*μg/l

TABLE 33. UP-FLOW CLARIFIER METALS SUMMARY ALUM TREATMENT NOVEMBER 1972 - OCTOBER 1973

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.0	0.0	0.0	0.0	0.0	9
Al	1.03	1.15	2.13	4.03	25.5	0.14	44
As*	5.8	5.2	6.8	5.2	25.0	0.0	77
B	0.37	0.36	0.37	0.08	0.55	0.12	74
Ba	0.040	0.041	0.057	0.058	0.41	0.01	68
Be*	0.0	0.001	0.0005	0.002	0.01	0.0	19
Ca	68.0	67.3	69.4	17.4	122.0	36.9	61
Cd*	4.0	4.0	4.1	1.8	11.0	0.0	93
Co	0.018	0.023	0.027	0.018	0.08	0.01	84
Cr	0.019	0.017	0.023	0.018	0.108	0.0	94
Cu	0.025	0.02	0.034	0.029	0.19	0.0	61
Fe	0.12	0.13	0.16	0.11	0.63	0.03	61
Hg*	0.09	0.15	0.32	0.84	4.40	0.0	46
K	12.3	12.5	12.5	1.1	14.4	11.2	9
Mg	4.50	4.54	4.58	0.59	5.91	3.81	23
Mn	0.040	0.032	0.037	0.017	0.090	0.003	62
Mo*	2.0	2.4	3.1	2.8	9.2	0.0	25
Na	88.5	87.5	89.3	17.7	132.0	49.0	48
Ni	0.060	0.058	0.068	0.041	0.33	0.0	62
Pb	0.030	0.035	0.042	0.030	0.16	0.01	93
Se*	0.0	1.2	1.0	1.5	7.0	0.0	62
Si	10.8	10.2	10.4	1.9	13.3	7.4	9
V*	4.0	3.6	3.9	1.4	6.2	1.4	15
Zn	0.070	0.108	0.109	0.13	0.88	0.01	61

Concentration in mg/l
*µg/l

TABLE 34. FILTER EFFLUENT METALS SUMMARY ALUM TREATMENT NOVEMEBER 1972 - OCTOBER 1973

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.0	0.0	0.0	0.0	0.0	8
Al	0.37	0.37	0.78	1.41	8.20	0.07	41
As*	5.0	4.8	6.1	5.0	26.8	0.0	71
B	0.39	0.38	0.38	0.08	0.62	0.19	68
Ba	0.040	0.039	0.056	0.061	0.38	0.0	62
Be*	0.0	0.004	0.012	0.016	0.03	0.0	5
Ca	66.0	66.3	68.6	18.9	148.0	35.0	57
Cd*	4.0	4.0	4.0	1.7	13.0	1.0	86
Co	0.019	0.023	0.027	0.017	0.080	0.011	77
Cr	0.013	0.013	0.019	0.016	0.096	0.0	86
Cu	0.036	0.03	0.056	0.123	0.94	0.0	57
Fe	0.10	0.11	0.13	0.11	0.69	0.03	57
Hg*	0.10	0.14	0.25	0.52	3.10	0.0	43
K	12.3	12.2	12.3	1.3	14.3	10.0	8
Mg	4.65	4.63	4.65	0.41	5.44	3.89	21
Mn	0.030	0.024	0.030	0.016	0.080	0.0	58
Mn*	2.5	2.4	3.8	5.1	25.2	0.0	23
Na	89.0	86.1	88.9	24.6	197.0	51.0	45
Ni	0.060	0.059	0.070	0.044	0.320	0.0	58
Pb	0.030	0.033	0.040	0.03	0.18	0.01	86
Se*	0.6	1.3	1.2	1.9	7.5	0.0	56
Si	10.0	9.6	9.7	1.9	12.0	7.2	9
V*	4.0	3.6	4.0	1.5	5.8	1.1	15
Zn	0.090	0.095	0.106	0.074	0.43	0.02	58

Concentration in mg/l
*μg/l

TABLE 35. CARBON COLUMN EFFLUENT METALS SUMMARY
ALUM TREATMENT NOVEMEBER 1972 - OCTOBER 1973

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.0	0.0	0.0	0.0	0.0	7
Al	0.13	0.20	0.60	1.75	10.80	0.07	39
As*	4.2	4.0	5.8	5.0	24.1	0.0	69
B	0.35	0.33	0.35	0.11	0.78	0.12	65
Ba	0.040	0.039	0.056	0.061	0.38	0.0	58
Be*	0.010	0.004	0.010	0.012	0.02	0.0	4
Ca	64.0	64.2	66.2	16.7	105.0	36.3	53
Cd*	3.0	3.0	3.8	2.9	25.0	1.0	83
Co	0.017	0.020	0.025	0.018	0.080	0.008	74
Cr	0.012	0.011	0.016	0.016	0.095	0.0	83
Cu	0.030	0.03	0.039	0.035	0.25	0.01	53
Fe	0.08	0.07	0.09	0.05	0.25	0.0	53
Hg*	0.11	0.13	0.22	0.41	2.25	0.0	38
K	12.0	11.6	11.6	1.3	13.0	8.9	7
Mg	4.68	4.51	4.55	0.54	5.32	3.23	20
Mn	0.020	0.016	0.023	0.016	0.081	0.0	54
Mo*	2.5	2.4	3.2	3.0	8.8	0.0	20
Na	89.0	84.5	86.4	18.0	125.0	49.0	41
Ni	0.050	0.046	0.058	0.040	0.27	0.0	54
Pb	0.030	0.032	0.040	0.03	0.16	0.0	83
Se*	0.0	1.1	0.6	1.0	5.0	0.0	54
Si	10.8	9.7	9.9	2.2	13.0	6.8	7
V*	4.0	3.8	4.3	2.0	8.3	1.7	13
Zn	0.055	0.058	0.067	0.044	0.250	0.0	54

Concentration in mg/l
*µg/l

sludge unit, and 32 percent and 27 percent through the Densator. Reductions in the Densator exhibited a concentration effect (r=0.75), and were proportional to effluent TSS (r=0.47) and reductions in phosphorus (r=0.12). The effluent concentrations of arsenic and phosphorus were also proportional (r=0.57). The latter correlation was anticipated, since both elements are adjacent members of Group 5A.

The multimedia filter removed 10 percent (mean) or 14 percent (median) of the influent arsenic, and the carbon column removed 5 percent (means) or 10 percent (medians), although no removal patterns or correlations were observed in either unit. The entire alum treatment train effected a net arsenic removal of 49 percent (mean) to 51 percent (median). Only 1 percent of the train influent samples exceeded the EPA drinking water MCL of 0.05 mg/l, with none of the succeeding samples ever reaching this value.

Frequency distributions for arsenic concentrations in the activated sludge influent and the product water are shown in Figure 32. Only about 2 percent of the samples in the activated sludge influent exceeded the National Interim Primary Drinking Water Regulations (NIPDWR) arsenic criterion and the median product water concentration was about one-tenth of the NIPDWR MCL.

Boron

Boron was refractory to the alum coagulation treatment sequence, the net mean and median removals being only 3 percent. Slight increases occurred through the Densator and filter, offset by removals in the activated sludge unit and carbon column. It should be noted that the magnitude of these variations is well within analytical error.

Barium

As the probability distributions in Figure 33 clearly demonstrate, both biological and chemical (alum) treatment removed some barium. Mean and median removals were 51 percent and 60 percent in the up-flow clarifier. Filtration and carbon adsorption had little, if any, effect on barium, and no removal patterns in any unit process could be identified. The highest observed concentration, found in the train influent, was only 0.48 mg/l--well below the EPA drinking water MCL of 1.0 mg/l.

Beryllium

Analysis for beryllium was performed once a week over a 6-month period from June through October of 1973. Only 15 out of 23 train influent samples had detectable concentrations, the highest being 0.04 μg/l. Only one out of nineteen Densator effluent samples contained beryllium in a detectable concentration, that being 0.01 μg/l Absolutely no correlations could be developed in the case of beryllium. There was a net mean reduction of 0.004 μg/l through the treatment train, but no change in the median concentrations.

Calcium

Activated sludge removal of calcium was 6 percent and 7 percent of the

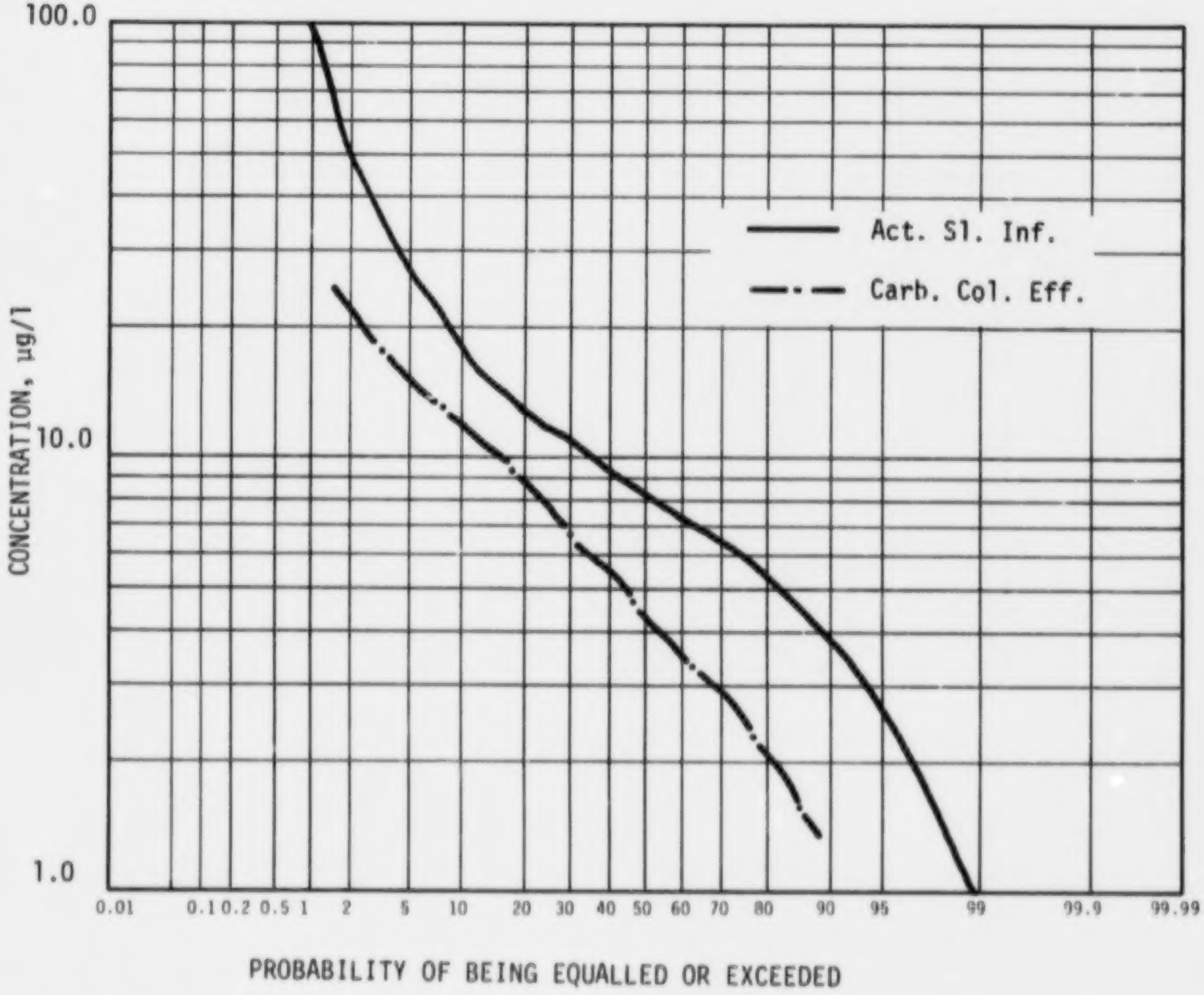

Figure 32. Selected frequency distributions for arsenic, alum coagulation study.

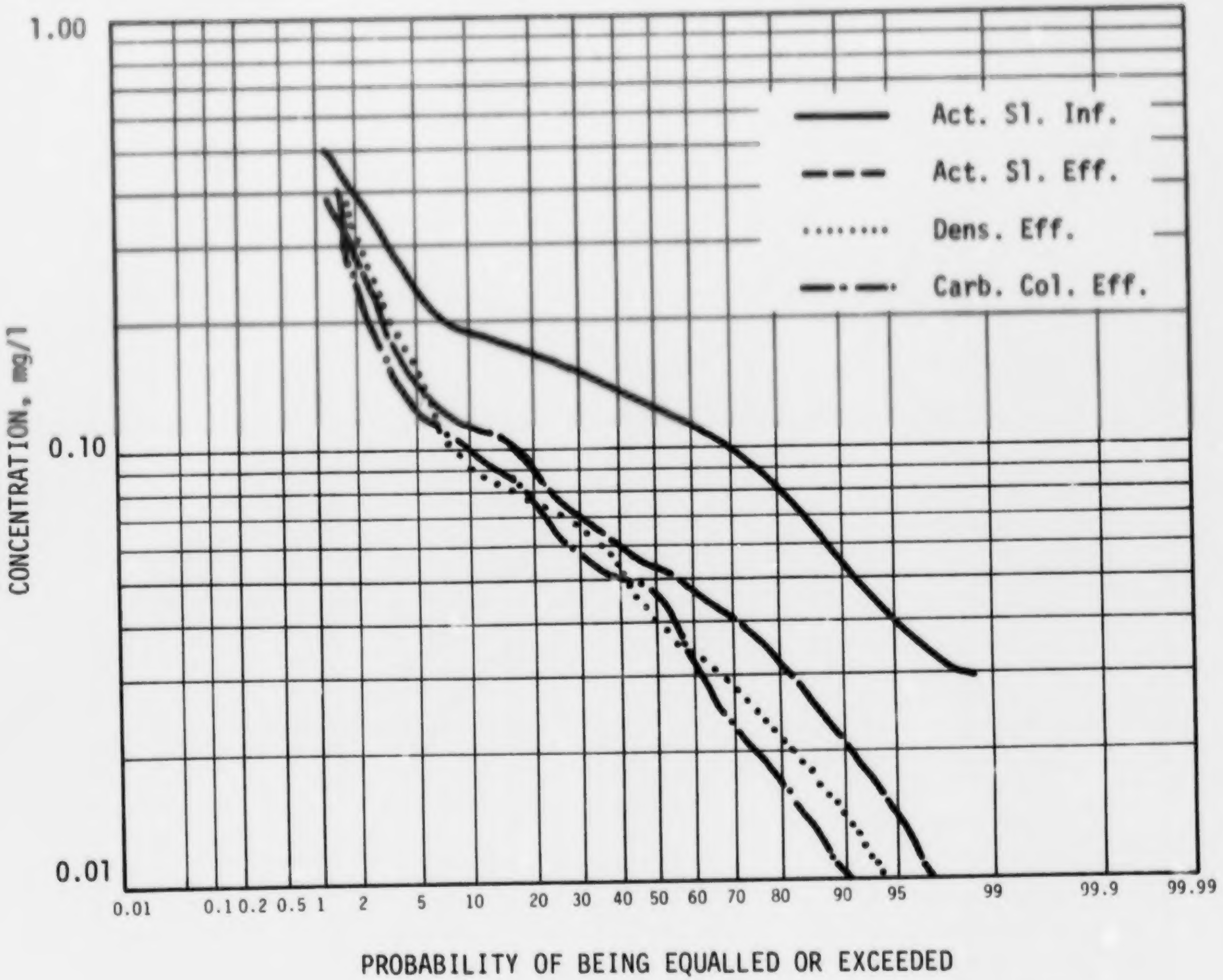

Figure 33. Selected frequency distributions for barium, alum coagulation study.

influent mean and median concentrations, respectively. Calcium was added by the Densator by the use of lime, the mean increase being about 13.6 mg/l. The calculated addition, based on the lime dose, was approximately 36 mg/l as calcium. Hence, 38 percent of the added calcium remained in solution, the remaining 62 percent apparently precipitated as sludge. It is noteworthy that these percentages coincide identically with those of the high-pH lime period (discussed in Section 6), where the lime dose was much higher. Only a samll amount of calcium was removed on the multimedia filter and carbon column. Calcium reductions through both units displayed weak tendencies toward a concentration effect, although no significant removal patterns were observed. Approximately 7 mg/l calcium was added to the water by the treatment sequence.

Cadmium

Frequency distributions for observed cadmium concentrations at various points in the treatment sequence are shown in Figure 34.

Cadmium was removed by both biological and chemical treatment, having mean and median removals of 54 percent and 55 percent in the activated sludge unit, 27 percent and 20 percent in the Densator. Reductions by alum clarification exhibited a concentration effect (r-0.64), but failed to correlate with suspended solids carryover, turbidity, chemical dose, or any other parameters. A slightly weaker concentration effect was seen on reductions through the multimedia filter (r=0.64), where the mean and median removals were but 4 percent and zero, respectively. Removal of cadmium through the carbon column was also relatively minor. The EPA drinking water MCL for cadmium of 0.01 mg/l was exceeded in 54 percent of the train influent samples and in 1 percent of the train effluent samples.

Cobalt

In contrast to the high-pH lime process, alum did not add cobalt to the water; however, the removals were quite small. Mean and median removals by activated sludge were 9 percent and 17 percent, respectively. There was a mean increase of 0.0009 mg/l through the Densator arising probably from cobalt contamination in the lime.

Relatively little change in cobalt concentrations occurred through the multimedia and carbon filters. Removals as high as 60 percent were obtained on virgin carbon, but fell off rapidly as the X/M increased. Reductions through the carbon also exhibited a very weak concentration effect. Train influent and effluent distributions are almost identical in the upper 30-percentile, but very dissimilar in the lower 70-percentile, as shown in Figure 35.

Chromium

Probability distributions for chromium concentrations are shown in Figure 36.

Mean and median removals of chromium were both 72 percent through

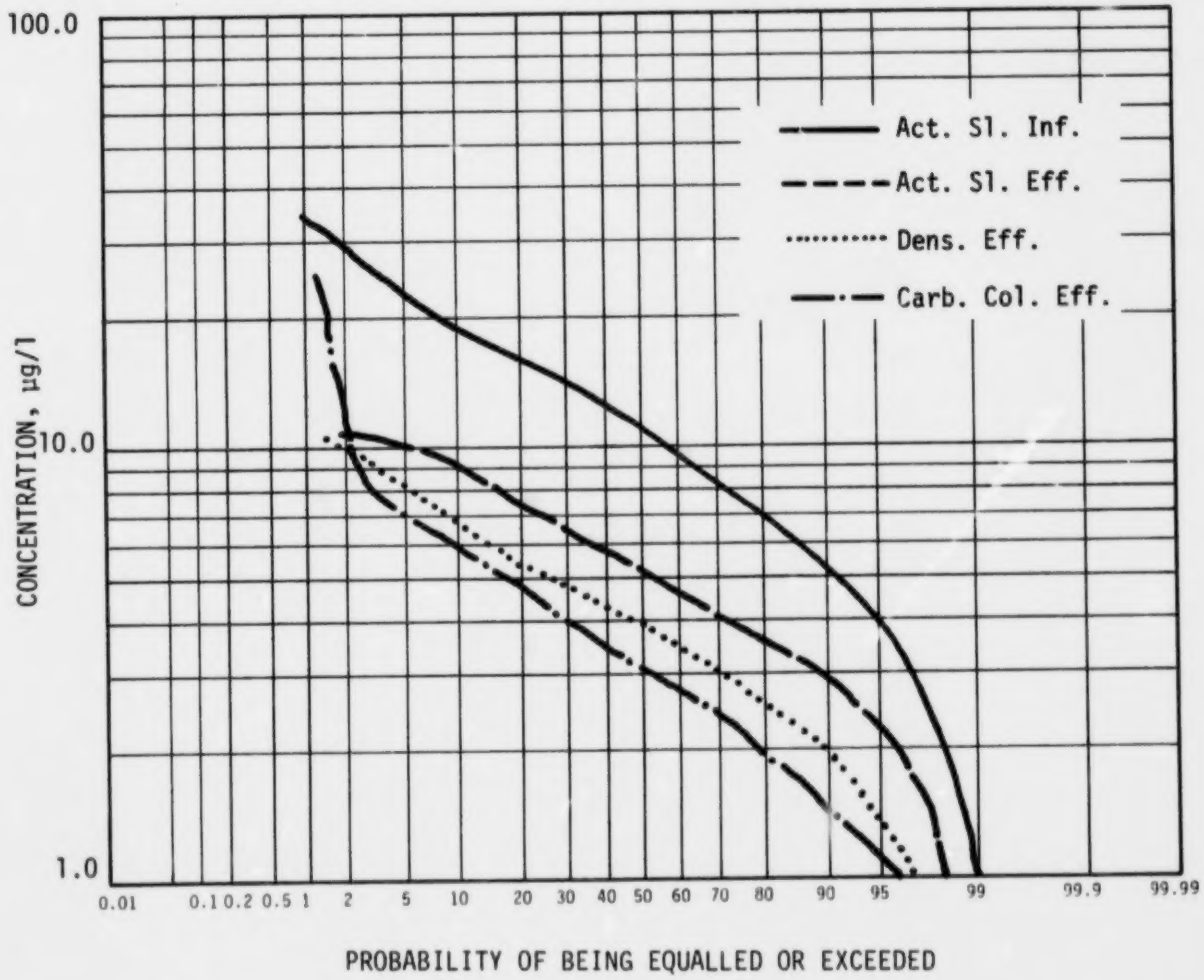

Figure 34. Selected frequency distributions for cadmium, alum coagulation study.

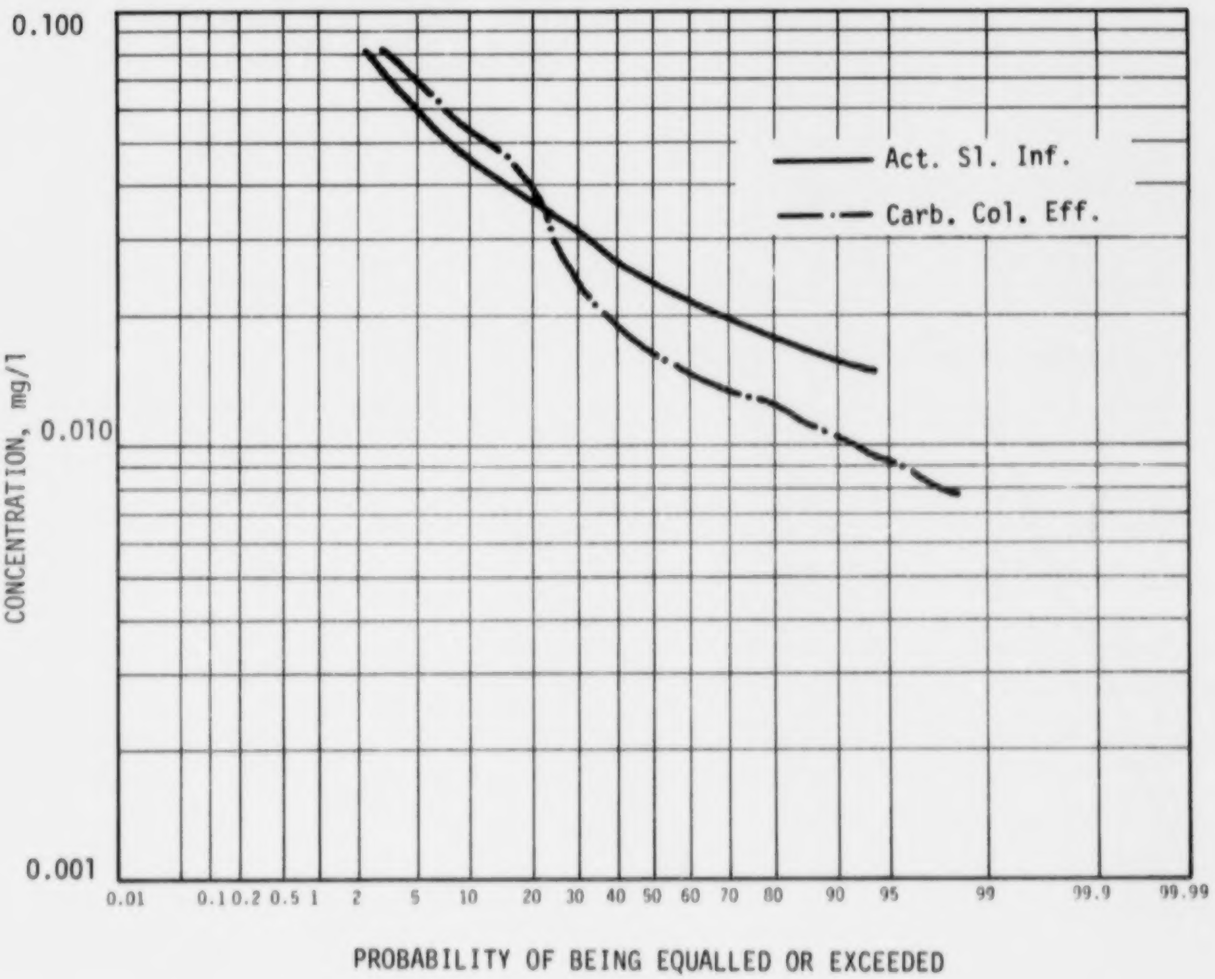

Figure 35. Frequency distributions for cobalt in sequence influent and effluent, alum coagulation study

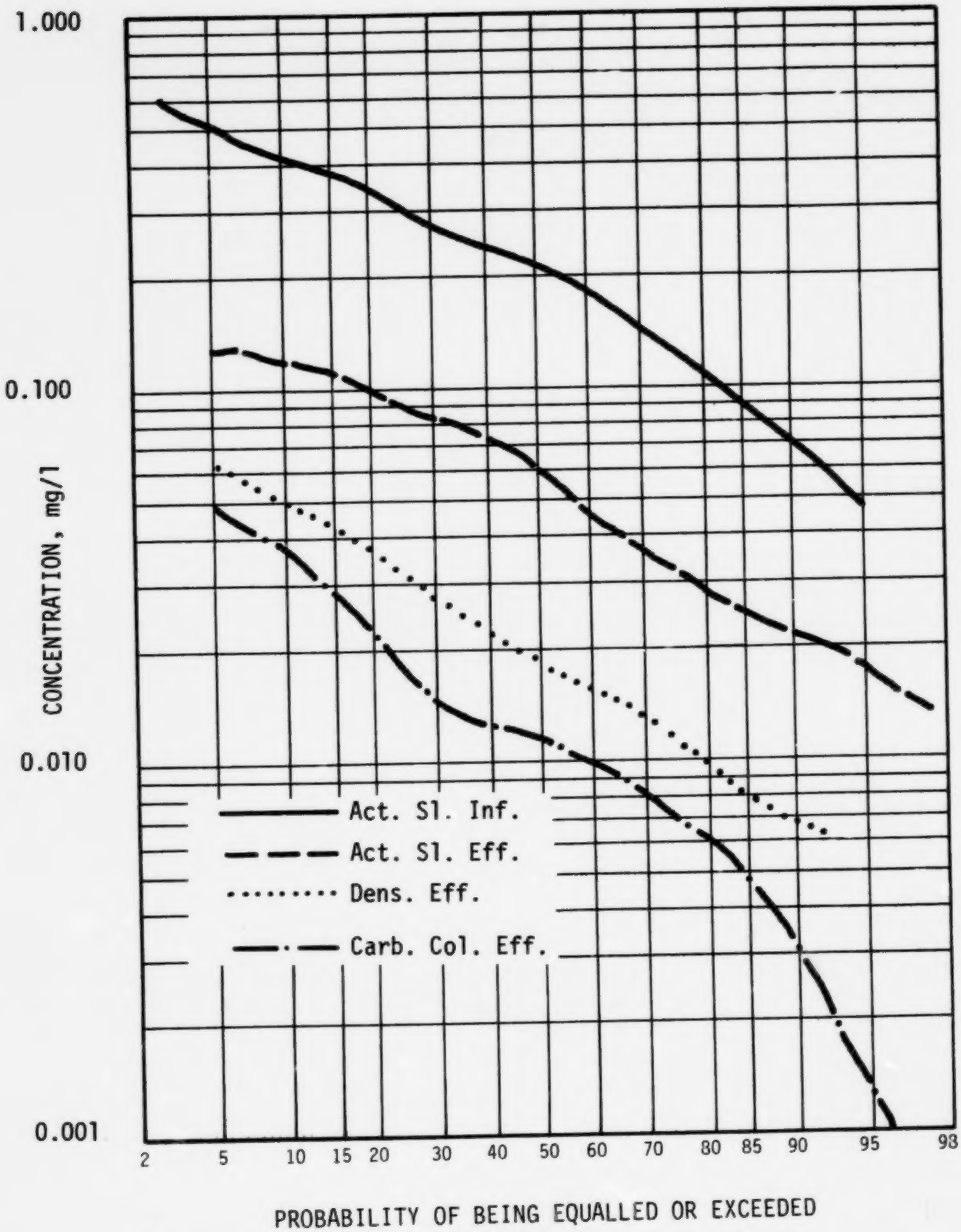

Figure 36. Frequency distributions for chromium, alum coagulation study.

activated sludge, and 65 and 69 percent through alum clarification. Reductions in the Densator exhibited a strong concentration effect (r=0.90), with a scattered but linear correlation between effluent phosphorus and chromium (r=0.23) concentrations.

Additional removals of a lesser magnitude were accomplished through filtration, 19 percent by means and 30 percent by medians. The chromium removal efficiency increased with TSS removal efficiency, and the reductions in chromium through the filter exhibited a concentration effect (r=0.51). Removal by carbon filtration averaged 13 percent (means) and 8 percent (medians), the reductions exhibiting a weak concentration effect (r=0.41), and falling off sharply at NH_3-N concentrations greater than about 1.5 mg/l. Approximately 95 percent of the train influent samples exceeded the EPA drinking water MCL of 0.05 mg/l for chromium and 2 percent of the train effluent samples exceeded the limit in spite of the relatively high net train removal of 93 percent (means) or 94 percent (medians).

Copper

The activated sludge unit was the most effective copper removal process, with mean and median removals of 84 and 83 percent respectively. Alum coagulation removed 37 percent (mean) and 50 percent (median) of the amount remaining. Exhaustive statistical work failed to correlate anything with copper, except that the reductions exhibited a minor concentration effect (r=0.28). Multimedia filtration imparted copper to the water, a phenomenon which is discussed more fully in Section 9. Most of the added increment, however, was taken out by the carbon column, where copper removals averaged 29 percent (mean) and 17 percent (median). Reductions through carbon exhibited a strong concentration effect (r=0.98), and again seemed to follow no other removal pattern. There were no extreme values in the train influent, but one out of 65 samples slightly exceeded the EPA Secondary Regulations recommendation of 1.0 mg/l.

Iron

Iron was removed by each process in the treatment train with the highest removals, 75 percent (mean) and 73 percent (median), in the activated sludge unit. Removals through the Densator averaged 51 percent (mean) to 63 percent (median), and were inversely proportional to effluent turbidity (r=-0.69), TSS (r=-0.36) and total phosphorus (r=0.22). Iron removal did not appear to be diminished unless effluent turbidity exceeded 1.2 FTU and/or TSS was greater than about 15 mg/l. A concentration effect on iron reductions was also observed (r=0.56).

Both mean and median removals through the multimedia filters averaged 17 percent, effluent iron being proportional to effluent TSS (r=0.61), and the reductions exhibiting a concentration effect (r=0.57). Carbon adsorption reduced the median concentration by only 0.20 mg/l, but reductions in extreme values averaged roughly 0.1 mg/l. With mean and median removals of 34 percent and 20 percent, carbon removed about 70 percent more iron than the multimedia filter. Reductions through carbon also exhibited a strong concentration effect (r=0.90).

The frequency distributions were log-normal on all sample sites within the train, and the net mean and median removals were both 93 percent. Approximately 98 percent of the train influent samples contained iron in excess of 0.3 mg/l, whereas none of the train effluent samples ever reached that level.

Mercury

As shown by the probability distributions in Figure 37, most of the mercury removal within the train was accomplished by the activated sludge process, 51 percent (mean) to 59 percent (median). Two extreme values in the Densator effluent resulted in an apparent mean increase of 0.06 µg/l, contrasted with a 40-percent median removal, the reductions exhibited a concentration effect (r=0.82). Increases in mercury occurred in 20 percent of the paired samples, always coinciding with low influent concentrations.

The median concentration remained at about 0.1 µg/l through filtration and carbon adsorption, while the mean removals were 23 percent and 9 percent, respectively. Reductions through both units exhibited concentration effects, with linear correlation coefficients of 0.66 for the filter and 0.83 for the carbon column. In spite of the rather large train removals of 57 percent (means) and 71 percent (medians), extreme values were carried all the way through the train. Approximately 4 percent of the train influent samples exceeded the EPA drinking water MCL of 0.002 mg/l, as did 3 percent of the train effluent samples.

Potassium

Small amounts of potassium were removed through the alum train. Mean removals were 5 percent by activated sludge, 1 percent by alum clarification, 2 percent by filtration, 5 percent by carbon adsorption, and 13 percent overall.

Magnesium

Magnesium like potassium, was partially and insignificantly removed through the alum train. The net mean and median removal efficiencies were only 5 percent and 2 percent, respectively.

Manganese

Almost equal amounts of manganese were removed by every unit in the treatment sequence. Mean and median removal efficiencies both averaged 34 percent in the activated sludge unit, and 32 percent and 25 percent in the Densator, the reductions in the latter exhibited a concentration effect (r=0.58). Removal efficiency was directly proportional to pH (r=0.37), the lowest removals occurring at pH <7.0, the highest removals at pH >8.0.

Multimedia filtration removed an additional 19 percent (median) to 26 percent (median), the reductions exhibited a concentration effect (r=0.52) and increased slightly with TSS removal efficiency. Carbon filtration removed 24 and 32 percent of its mean and median influent concentrations.

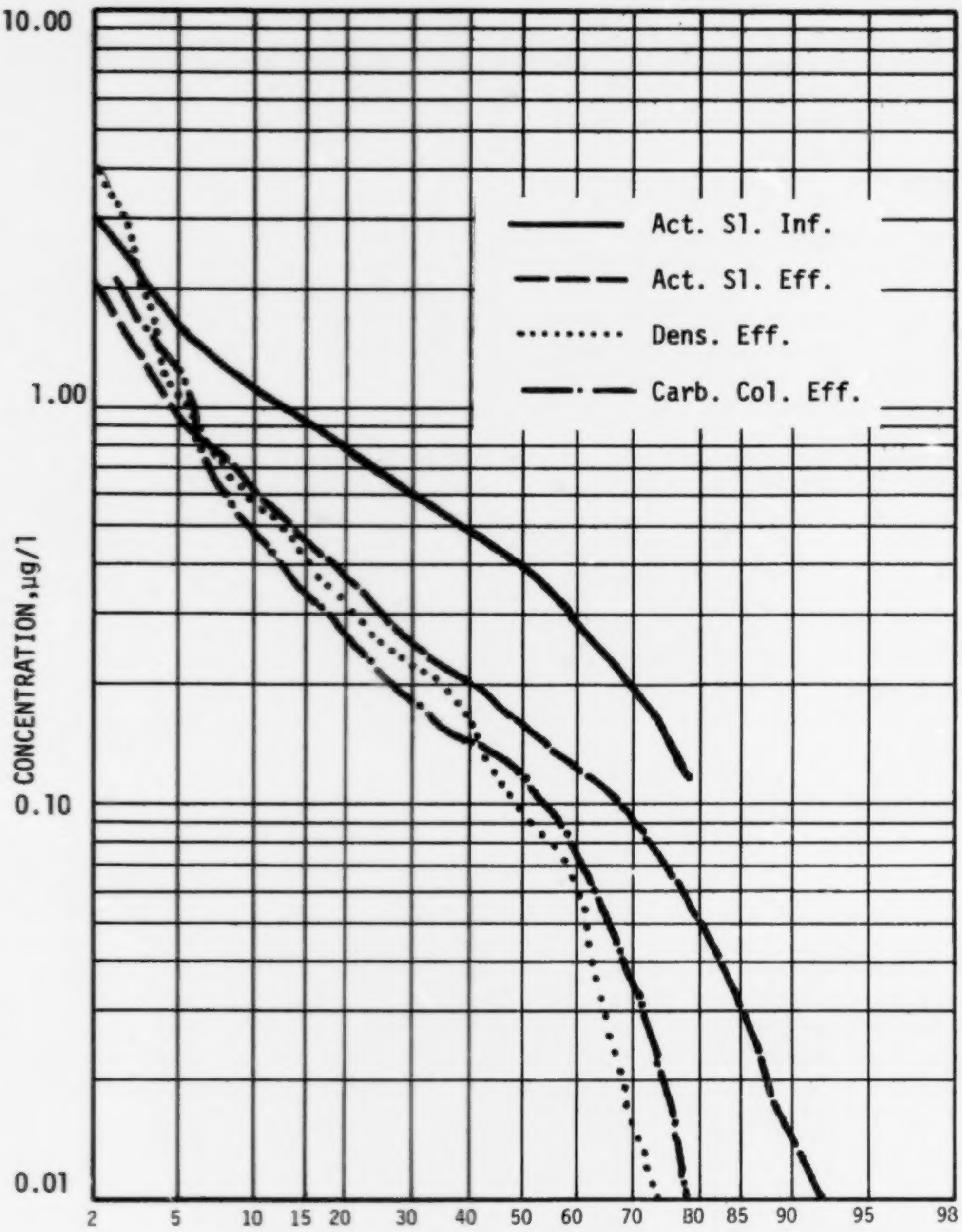

Figure 37. Frequency distributions for mercury, alum coagulation study.

The net train removals of manganese came to 73 percent (mean) and 75 percent (median). It appears, however, that the reductions through the treatment sequence were relatively constant at about 0.06 mg/1, regardless of the influent concentration. The Secondary Regulations recommendation of 0.05 mg/1 was exceeded by 100 percent of the train influent samples and 4 percent of the train effluent samples.

Molybdenum

The activated sludge unit removed 94 percent of the total molybdenum removed by the alum treatment sequence. The removal efficiency through the unit was 80 percent (means) and 79 percent (medians). Alum coagulation reduced the concentration by about 1 μg/1 which represents a removal efficiency of 26 percent (means and medians). The reductions were linearly dependent upon the influent concentrations (r=0.70), and declined sharply as effluent TSS exceeded about 10 mg/1.

During multimedia filtration there were mean and median increases of 22 percent and 25 percent, followed by removals of 16 percent and 2 percent during carbon filtration. Overall, the train effected a mean removal of 85 percent and a median removal of 81 percent. Frequency distributions for molybdenum are shown in Figure 38.

Sodium

Sodium was neither added nor removed during alum treatment. Overall, there was a 6 percent mean and a 2 percent median removal through the treatment sequence, the highest removals occurred in the activated sludge and carbon column units. The maximum train effluent concentration was 125 mg/1, which exceeded the mean concentration by about 45 percent.

Nickel

Almost 2/3 of the nickel removed in the alum train was accomplished during biological treatment. The Densator removed 14 percent of the mean and median concentrations. Multimedia filtration failed to change the median nickel concentration, but there was a slight (3 percent) increase in the mean. Carbon adsorption removed an additional 17 percent by both mean and median, the reductions exhibiting a concentration effect (r=0.50). The frequency distribution on all effluents appeared to be bimodal and devoid of extreme values, as indicated in Figure 39.

Lead

As those data in Figure 40 indicate, lead was removed chiefly in the activated sludge unit, but some removal was observed in the Densator. Mean and median removals were 56 percent and 64 percent through activated sludge, 22 percent and 25 percent through alum clarification. Reductions in the latter exhibited a concentration effect (r=0.42), and in general appeared to decline with the occasional turbidity and suspended solids breakthroughs. Multimedia and carbon filtration effected only minor removals, in many cases zero or negative.

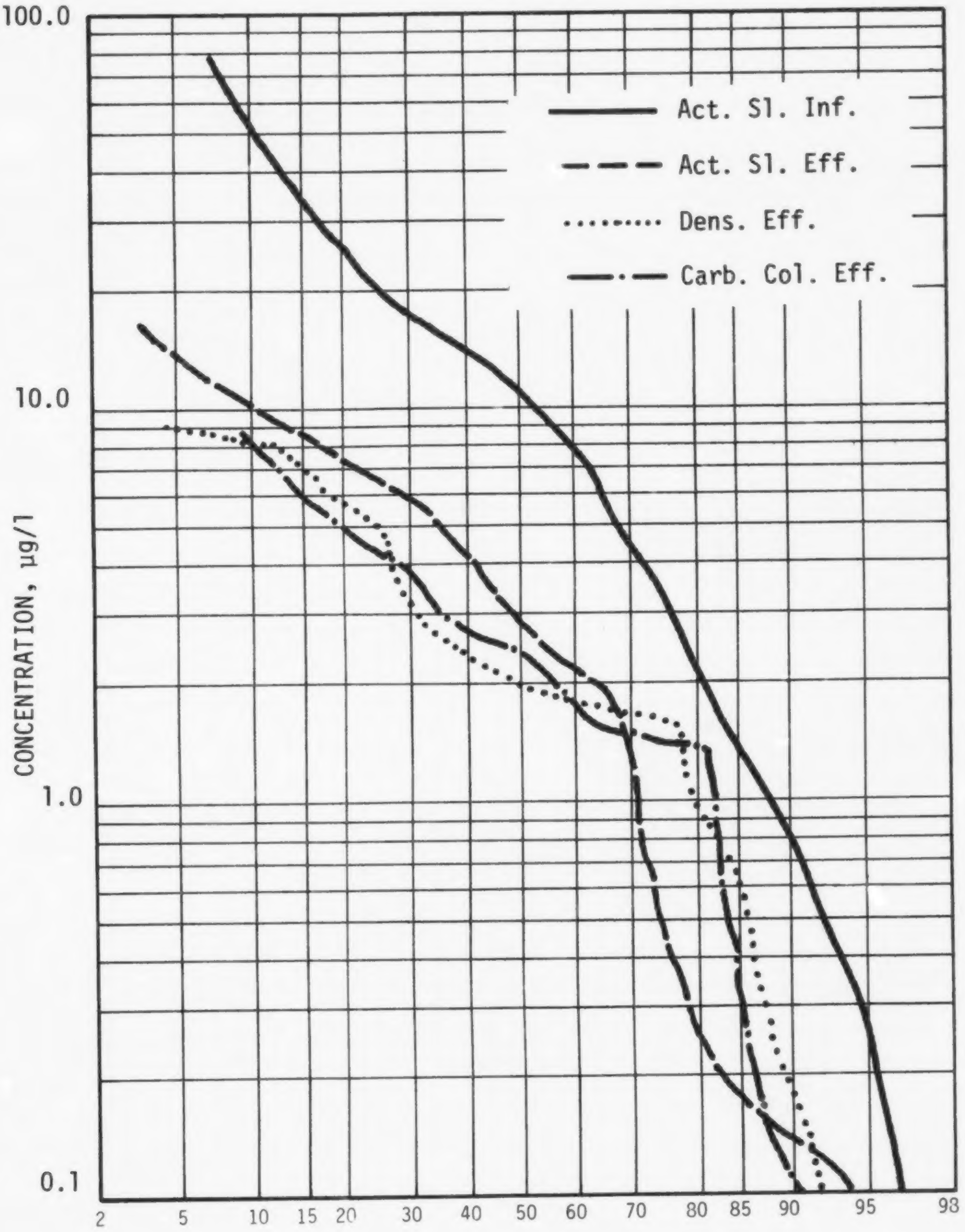

Figure 38. Frequency distributions for molybdenum, alum coagulation study.

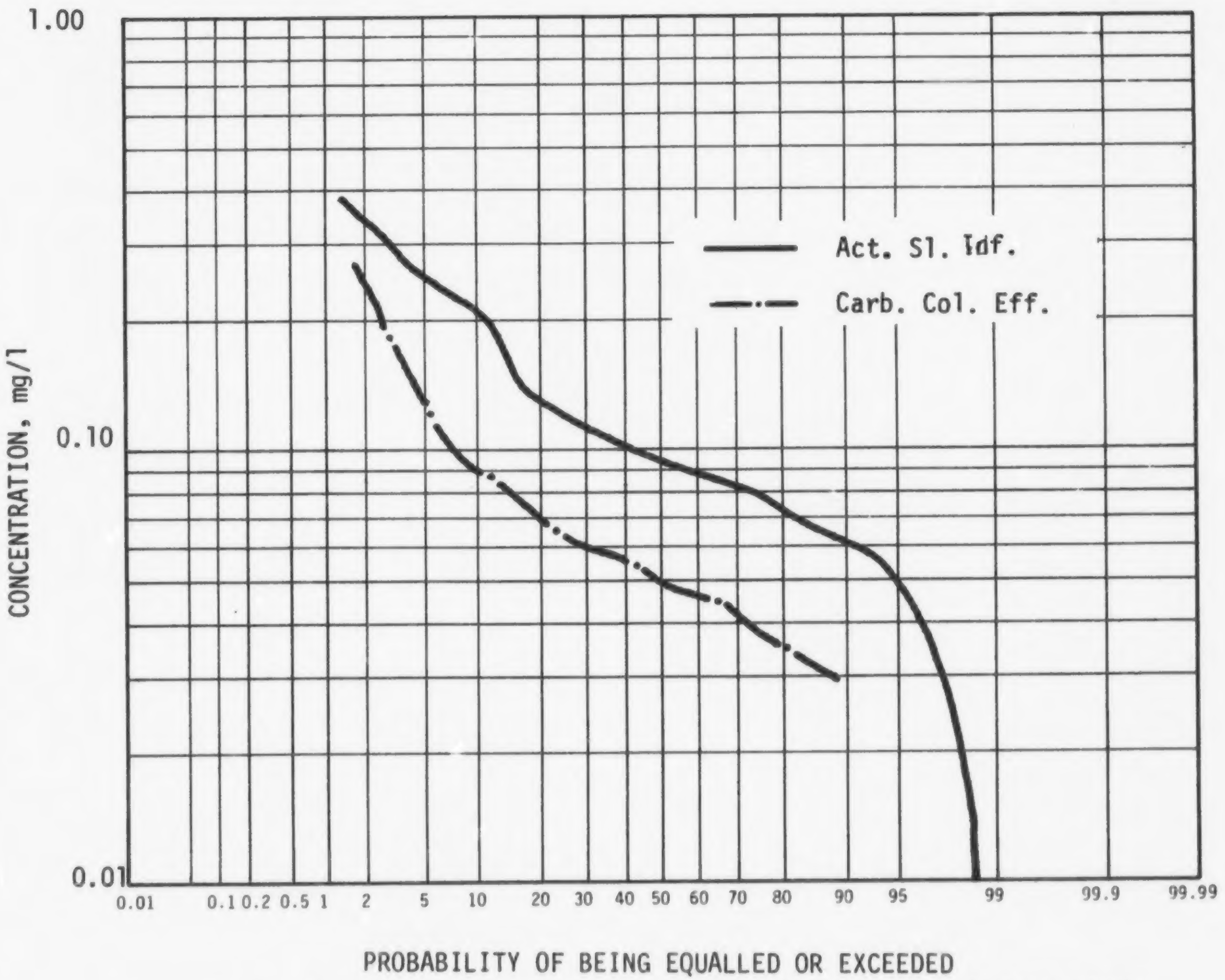

Figure 39. Frequency distributions for nickel, alum coagulation study.

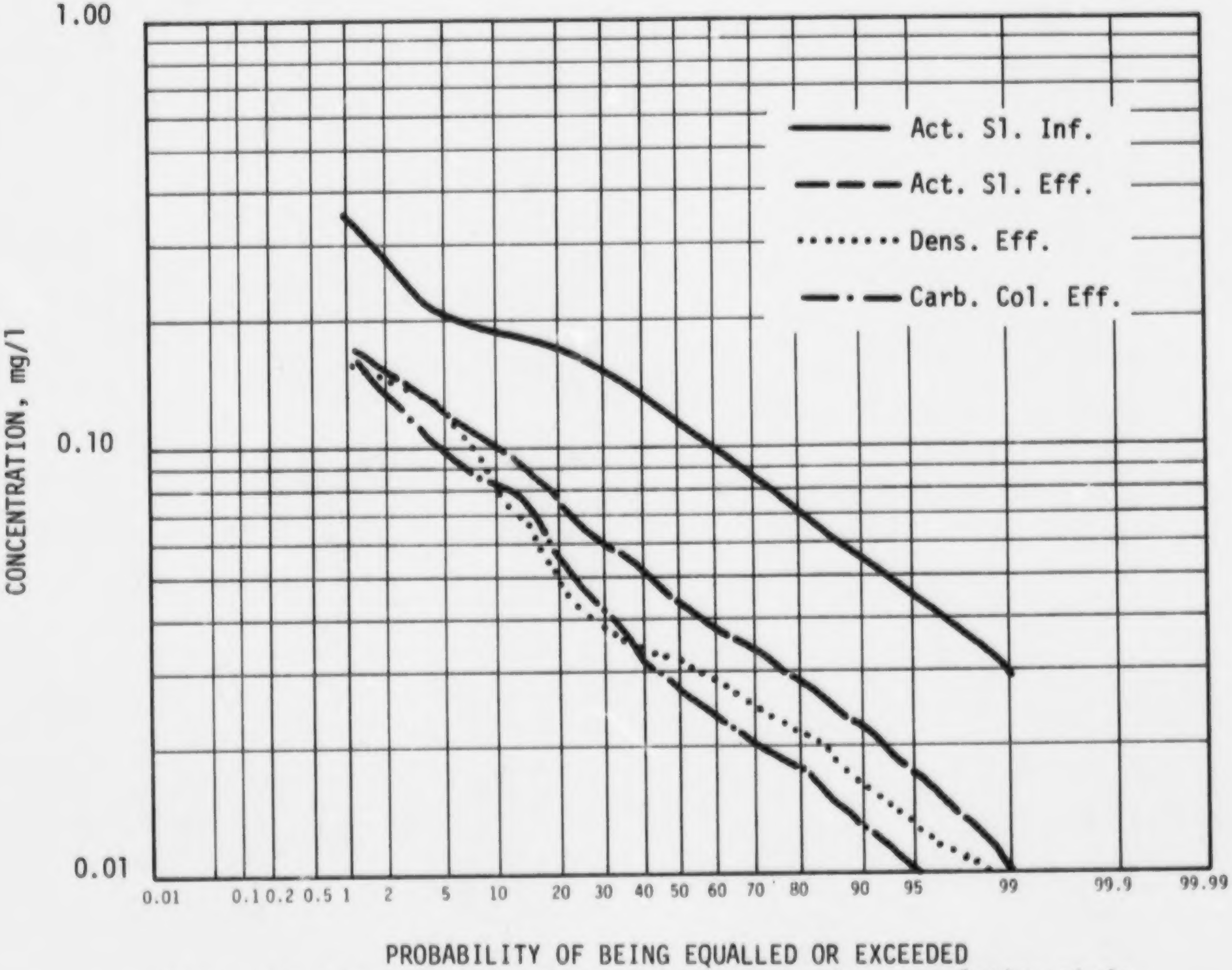

Figure 40. Frequency distributions for lead, alum coagulation study.

The distribution of lead at all sample sites was log-normal with no extreme values. The EPA drinking water MCL of 0.05 mg/l was exceeded in 91 percent of the train influent samples and in 22 percent of the train effluent samples.

Selenium

Mean and median removals of selenium through the activated sludge unit were 77 and 83 percent, respectively. Chemical treatment effected a mean removal of 11 percent while the median concentration dropped from 0.5 µg/l to zero, indicating 100 percent removal. Approximately 48 percent of the Densator effluent samples had nonzero concentrations of selenium i.e., greater than the observable detection limit of 1 µg/l.

The mean selenium concentration appeared to increase during filtration and drop during carbon adsorption. The former case is a reflection of extreme values in the upper ten percentile, whereas the mean removal through carbon adsorption (52 percent) was sufficient to overcome the apparent addition in the filter. Reductions in concentration through the carbon column exhibited a well-defined concentration effect (r=0.79). Eleven percent of the train influent samples exceeded the NIPDWR standard of 0.10 mg/l, compared to zero percent in all succeeding samples. Frequency distributions are shown in Figure 41.

Silicon

Little or no removal of silicon occurred within the alum treatment train. The multimedia filter, which effected a larger removal than the other unit processes, removed only 10 percent (mean) or 7 percent (median). Overall, there was a 3-percent mean removal and a 10-percent median addition through the train.

Vanadium

Vanadium was slightly removed, but only by biological and chemical treatment. Mean and median removals were 13 percent and 15 percent through the activated sludge unit, 8 and 9 percent through the Densator, 12 and 23 percent through the entire train. The removals failed to correlate with other parameters.

Zinc

During the months of December 1972 through May 1973 there were six occasions when the train influent contained more than 1.0 mg/l zinc. These were the only months in the 20-month period in which this occurred. It was assumed that these incidents were related to industrial activity. In all cases the activated sludge unit was able to significantly reduce the effluent concentration to ambient, or average background levels. The greatest removals within the treatment train occurred in the activated sludge unit, 70 percent by means and 63 percent by medians. Mean and median removals during chemical treatment were 30 and 42 percent, respectively. Reduction through the Densator exhibited a concentration effect (r=0.70), and removal efficiency dropped off sharply when effluent turbidity exceeded about 2.0 FTU.

Multimedia filtration removed about 3 percent (mean) of the zinc, yet there was a simultaneous increase of 0.02 mg/l (by median). It appears that there was not a substantial shift in concentrations, although the filter did a good job of damping extreme values. The reductions in zinc by filtration exhibited a strong concentration effect (r=0.87). Removal of zinc by carbon adsorption was consistent, and averaged 37 percent more by carbon adsorption than by multimedia filtration, and the reductions were concentration-dependent (r=0.77). Also, the removals and reductions of zinc were proportional to the organic loading on the carbon (X/M), indicating a possible organic ligand effect. All sample sites except the train effluent had varying degrees of extreme values whose distribution patterns were difficult to identify. However, the final effluent distribution can be considered log-normal. The maximum concentration of zinc ever observed was 4.1 mg/l (train influent); hence, all samples were well below the Secondary Regulations recommendation of 5.0 mg/l.

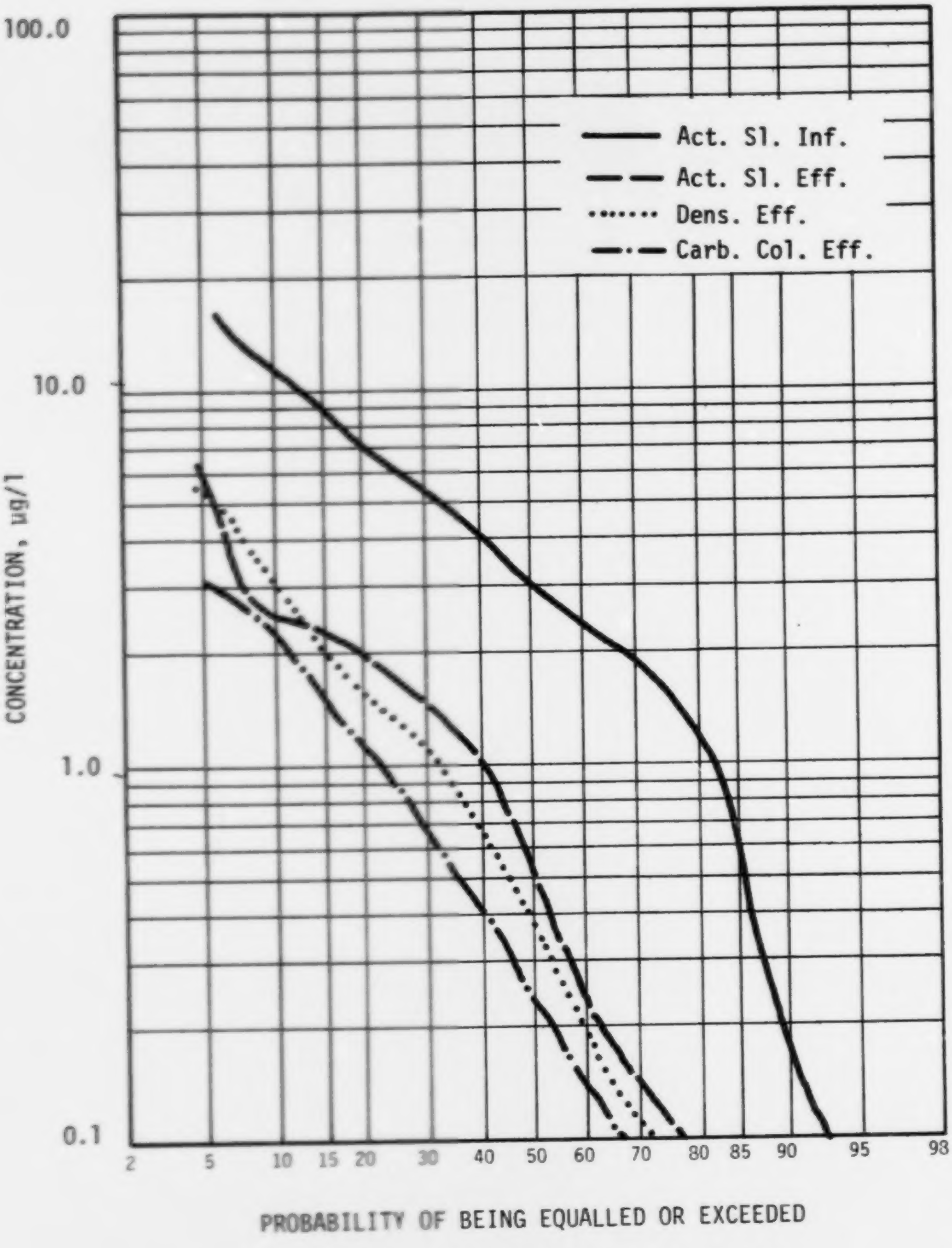

Figure 41. Frequency distributions for selenium, alum coagulation study.

SECTION 8

HIGH-pH LIME COAGULATION AND SINGLE-STAGE RECARBONATION

GENERAL

This phase of the research effort was necessitated by the absence of any effluent pH adjustment in the previous high-pH lime coagulation study. Since it is neither practical nor desirable to discharge an effluent with a median pH value of 11.5, and since the possible effects of the high-pH effluent on the performance of the filtration and adsorption processes were relatively undefined, the decision was made to repeat the high-pH lime coagulation studies and incorporate single-stage recarbonation.

The alum coagulation study was terminated on October 30, 1973, at which time the up-flow clarifier was drained, washed down, and promptly returned to service for operation in the high-pH lime coagulation mode.

The single-stage recarbonation basin was fabricated from a galvanized steel tank and a CO_2 diffusion grid was made of 1/2-inch PVC drilled with small holes. Pure CO_2 was metered from a 5,700 kg (12,500 lb.) receiver into the bottom of the tank through a pressure regulator and flowmeter. Feed pressure was always in excess of 50 psi, and rate was adjusted by the operator as required in order to maintain an effluent pH of 6.5 to 7.0. The up-flow clarifier effluent flowed by gravity into the bottom of the recarbonation basin and over-flowed out the top through a V-notch weir which produced a co-current contacting arrangement. The neutralized effluent was then pumped to the No. 1 multimedia filter.

The recarbonation basin was operated off-line from November through December 9 for de-bugging purposes. During this time a portion of the high-pH effluent went to the recarbonation basin, and the other portion was routed to the filter gallery for filtration and carbon adsorption. On December 10 the recarbonated effluent was piped into the filter gallery for the first time, and this operating mode was maintained until the termination of the project. The inclusive dates for the recarbonated high-pH lime coagulation study were November 2, 1973 through January 31, 1974, although the filter and carbon column did not come on line until December 10. Because this was a relatively short period of investigation, the sampling frequency for metals analyses was increased from twice per week to daily, and the individual processes were monitored very closely to assure good process control.

The process configuration and mean flows through the respective unit processes are shown in Figure 42. As in the two previous phases of the project, the most significant process change was in the chemical treatment utilized.

The performance of the treatment sequence was excellent, and Table 36 presents an abbreviated summary of the means of selected water quality parameters. COD, BOD_5, and TSS concentrations all exhibited reductions greater than 98.4 percent. The reductions in bacterial densities were very good, although not as dramatic as the kills observed during the high-pH lime coagulation phase. This particular point will be addressed in the following sections.

Figure 43 presents frequency distributions for the observed COD concentrations in the raw wastewater, the activated sludge effluent, and the final product water. When presented in this manner, the relative improvement in water quality due to secondary treatment, and due to advance wastewater treatment can be readily assessed. The median COD concentrations for the raw wastewater, activated sludge effluent, and carbon column effluent were 500, 45, and 5 mg/l, respectively. These data indicate excellent process performance and an overall COD reduction of about 99 percent. Extreme values did exist in the observed COD concentrations. The ninety-five percentile values indicated a product water COD concentration of 60 mg/l; however, the corresponding COD in the activated sludge effluent was 120 mg/l, and the raw wastewater COD was approaching 1000 mg/l. Under these conditions the AWT processes provided a COD reduction of 60 mg/l, or a 50-percent reduction in the COD of the activated sludge effluent.

Figure 44 presents the probability distributions for observed TSS concentrations at selected points in the treatment sequence. These data indicate that control of product water suspended solids was very effective. The median TSS concentration in the product water was 3 mg/l (4 mg/l mean), and in 40 percent of the samples there were no detectable suspended solids.

COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM

During this portion of the research effort the performance of the completely-mixed activated sludge (CMAS) system was not as good as one would have liked in that the effluent TSS averaged 44 mg/l, which resulted in effluent BOD_5 and COD concentrations of 38 and 65 mg/l, respectively. The performance is summarized in Table 37, and the hydraulic operation and process control parameters are given in Table 38.

During this portion of the study the mean sludge age was 13.2 days and the wastewater temperature averaged 21°C. The major operational difficulty experienced was obtaining good liquid/solids separation in the secondary clarifier, since the mixed liquor was denitrifying and rising to some degree during most of this phase of the project. The return sludge flow was increased in an effort to remove the sludge from the anaerobic conditions in the clarifier bottom as quickly as possible; this action did significantly improve the problem of rising sludge. A subjective evaluation of the operation of the activated sludge system indicates that the sludge age was

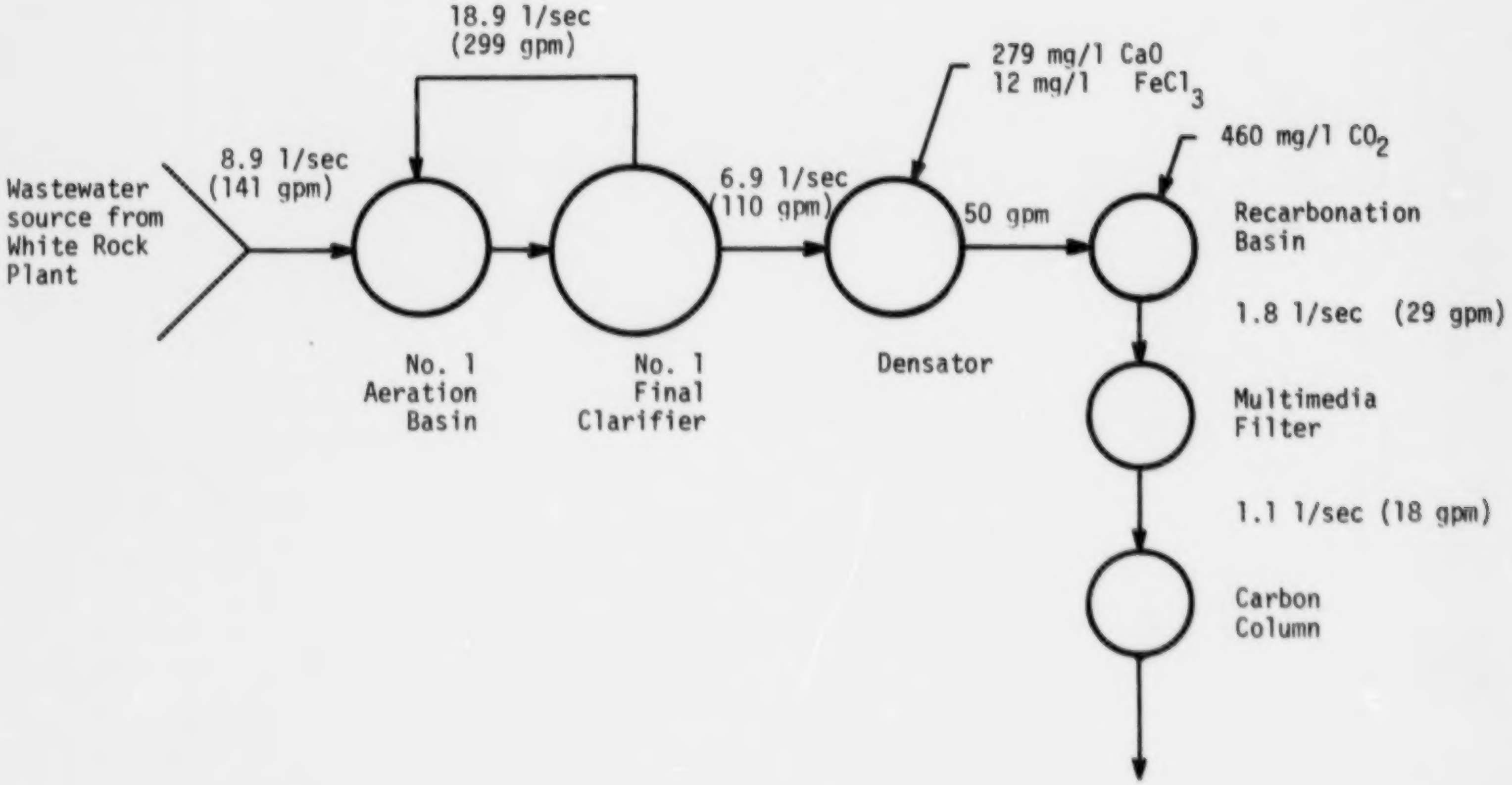

Figure 42. Process configuration: High-pH lime coagulation and single stage recarbonation; November 2, 1973 - January 31, 1974

TABLE 36. SUMMARY OF WATER QUALITY DATA FOR THE HIGH-pH LIME COAGULATION AND RECARBONATION STUDY.

Parameter	Raw Waste Water (mg/l)	Final Product (mg/l)	Removal (percent)
COD	526	8	98.5
BOD_5	198	2	99.0
TSS	245	4	98.4
TDS	742	637	14.2
NH_3-N	17.0	2.7	84.1
Org. N	11.9	1.1	90.8
NO_2 & NO_3-N	< 0.5	10.8	N/A
NO_2-N	--	0.12	N/A
Total P	--	0.9	N/A
pH, Units	7.5	6.8	N/A
Std. Plate Count per ml	--	3.3×10^3	N/A
Total Coliforms per 100 ml	--	1.3×10^2	N/A
Fecal Coliforms per 100 ml	--	59	N/A

N/A: Not Applicable

-- : Not Available

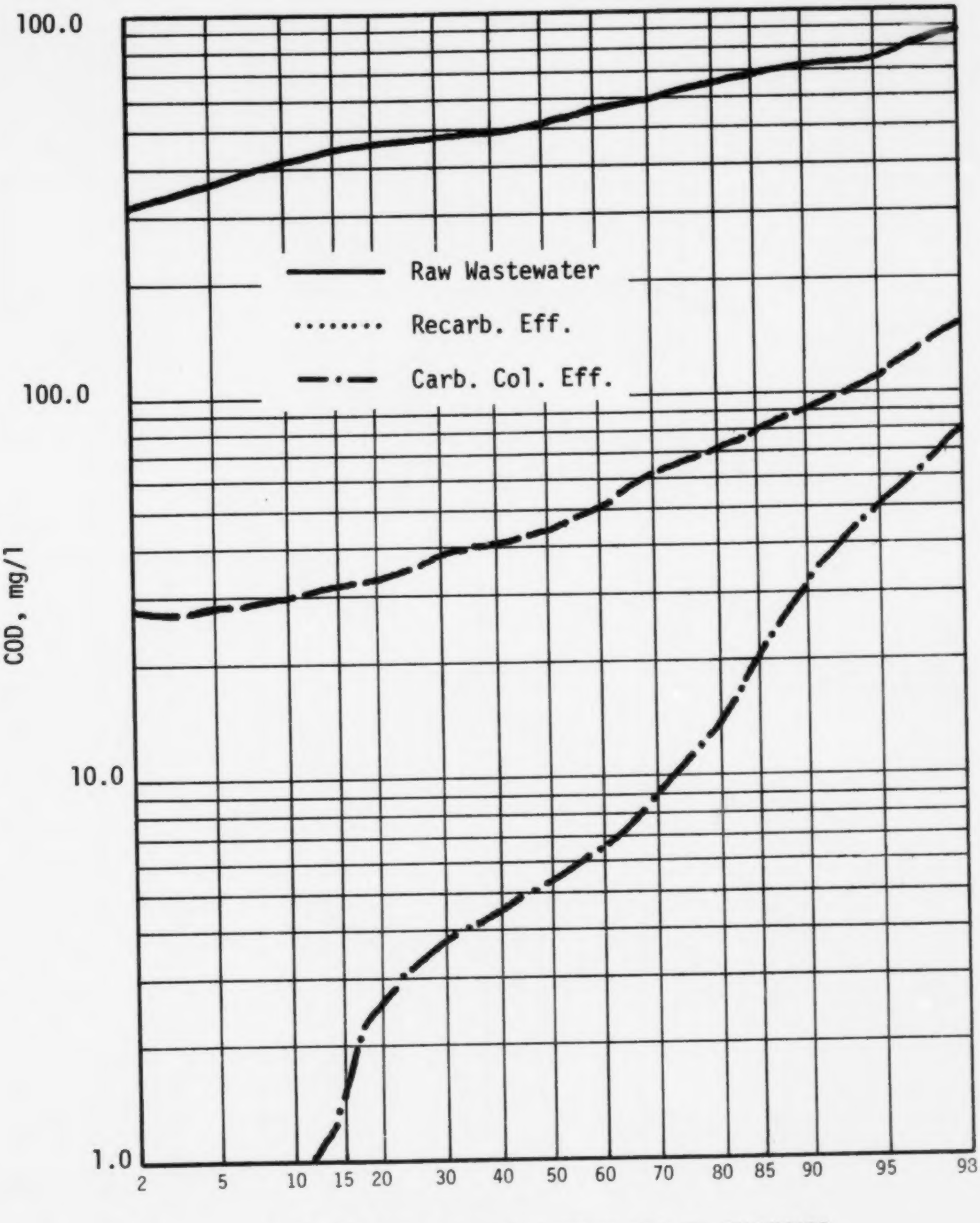

Figure 43. Frequency distributions for selected COD data; high-pH lime coagulation and recarbonation study.

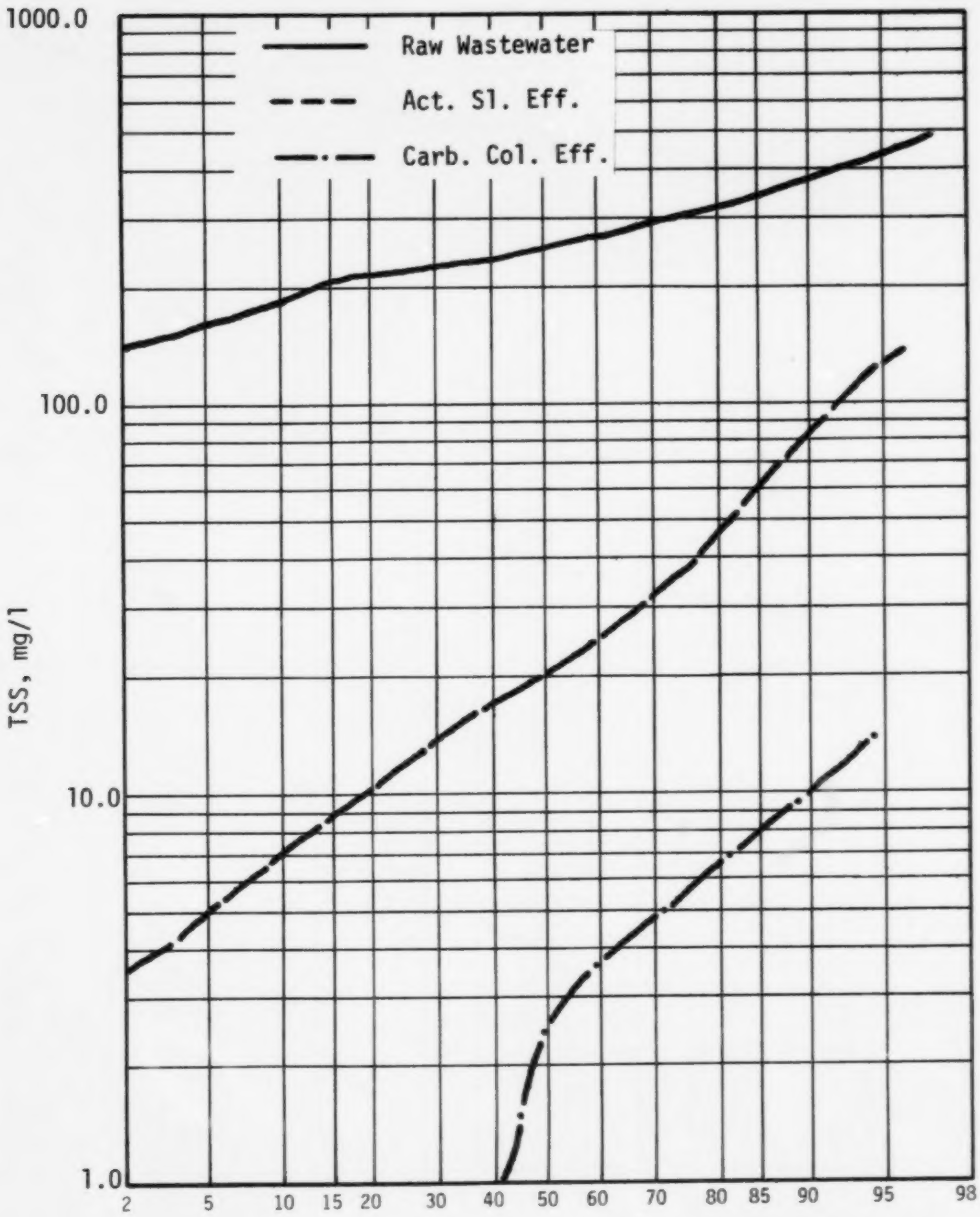

Figure 44. Frequency distributions for selected TSS data; high-pH lime coagulation and recarbonation study.

TABLE 37. PERFORMANCE SUMMARY OF THE COMPLETELY-MIXED ACTIVATED SLUDGE SYSTEM, HIGH-pH LIME COAGULATION AND RECARBONATION STUDY.

Parameter	Activated Sludge Influent (mg/l)	Activated Sludge Effluent (mg/l)	Reduction (percent)
COD	217	65	70.0
TOC, Soluble	27	11	59.3
BOD_5	69	38	44.9
TSS	133	44	66.9
TDS	557	536	3.8
SC µmho/cm	851	762	10.5
NH_3-N	14.5	1.9	86.9
Org. N	9.1	4.4	51.3
NO_2+NO_3-N	0.9	9.9	N/A
NO_2-N	0.11	0.053	51.8
Total P	10.2	7.4	27.5
pH, units	7.2	7.1	N/A
T. Alk., as $CaCO_3$	215	129	40.0
P. Alk., as $CaCO_3$	0	0	0
Std. Plate Count per ml	1.9×10^6	9.3×10^3	99.5
Total Coliforms per 100 ml	1.4×10^7	3.2×10^5	97.7
Fecal Coliforms per 100 ml	4.2×10^6	2.5×10^4	99.4

N/A : Not Applicable

TABLE 38. PROCESS SUMMARY FOR THE COMPLETELY - MIXED ACTIVATED SLUDGE SYSTEM, HIGH-pH LIME COAGULATION AND RECARBONATION STUDY

HYDRAULIC OPERATION	
Q (influent)	8.9 l/sec (141 gpm)
Q (influent)	11.2 l/sec (180 gpm)
Q (waste)	2797 l/day (739 gpd)
Aeration T	1.70 hour
Clarifier Overflow Rate(Q_i)	11.7 m^3/day-m^2 (287 gal/ft^2 -day)
Weir loading	27.7 m^3/day-m (2231 gal/ft-day)
Clarifier T ($Q_i + Q_r$)	3.3 hours
Clarifier T (Q_i)	7.5 hours
PROCESS CONTROLS	
MLSS	4287mg/l
MLVSS	2915 mg/l
RAS	7649 mg/l
SVI	196 mg/l
Air supplied	23.32 l/sec (494 scfm)
D. O.	4.7 mg/l
D. O. Uptake Rate	25.8 mg/l-hr.
F/M (COD)	0.288 day $^{-1}$
F/M (SOC)	0.028 day $^{-1}$
F/M	0.073 day $^{-1}$
Sludge Age	13.2 days
Temperature	21° C (70° F)

probably 3 to 5 days too old during this time, and increased sludge wastage would probably have improved system stability.

Nitrification was desired during this phase of the project; however, the arithmetic mean of 1.9 mg/l NH_3-N in the effluent indicates that nitification was rather erratic. Figure 45 presents probability distributions for the NH_3-N data at selected points in the treatment sequence. It is interesting to note the large difference between the mean (1.9 mg/l) and the median NH_3-N concentration of 0.2 mg/l. The agreement between the mean NO_2 & NO_3-N concentration of 9.9 mg/l, and the median concentration (about 12 mg/l) is much better. The data in Figure 46 indicate that these data closely approximate log-normal probability distributions, and the mean and median values should be reasonably close.

As stated earlier the average COD and BOD_5 concentrations were high, 65 and 38 mg/l, respectively, and the problem was attibuted to poor liquid-solids separation in the final clarifier. The data in Figure 47 clearly indicate the affect that effluent TSS had on the effluent COD.

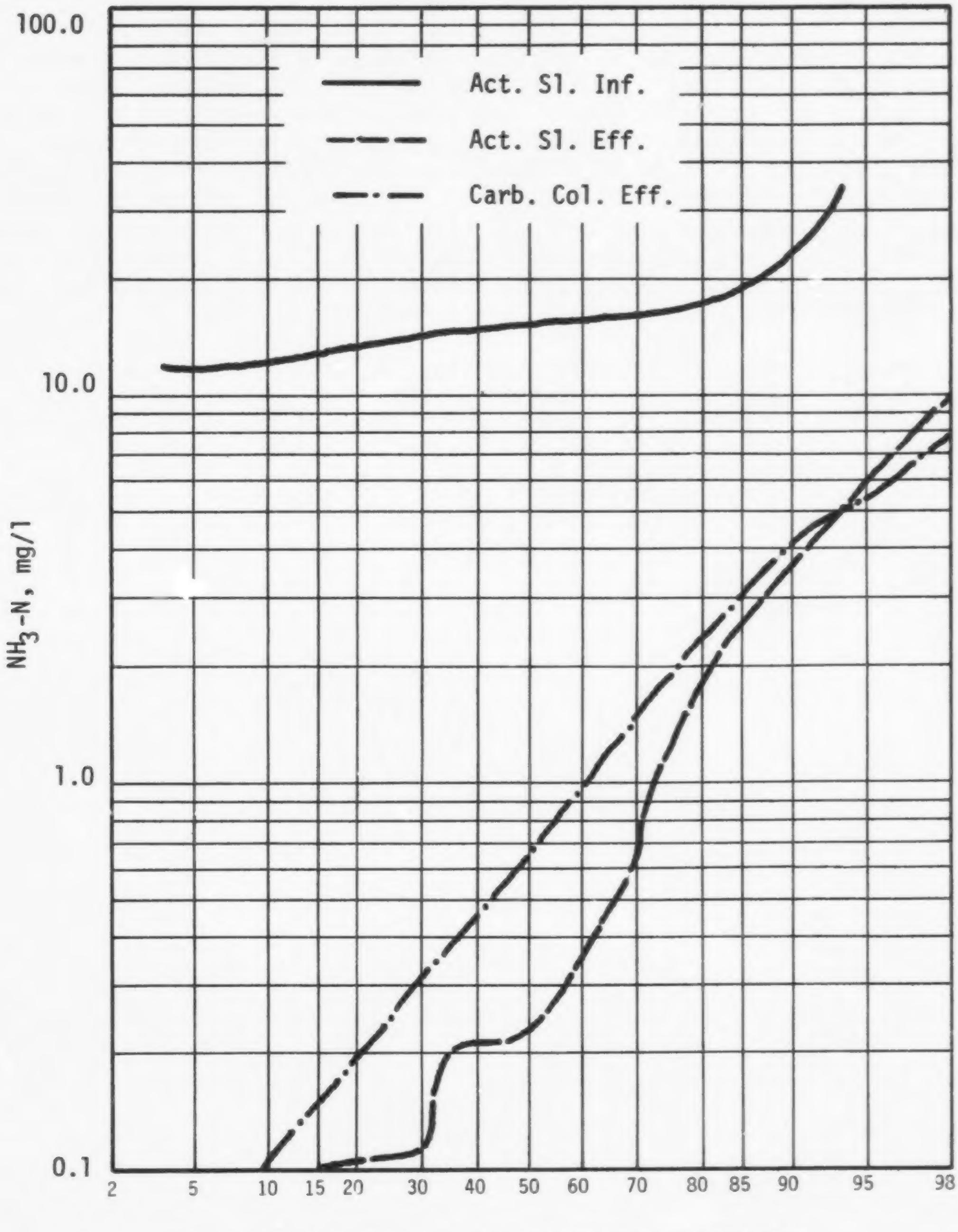

Figure 45. Frequency distributions for selected NH_3-N data; high-pH lime coagulation and recarbonation study.

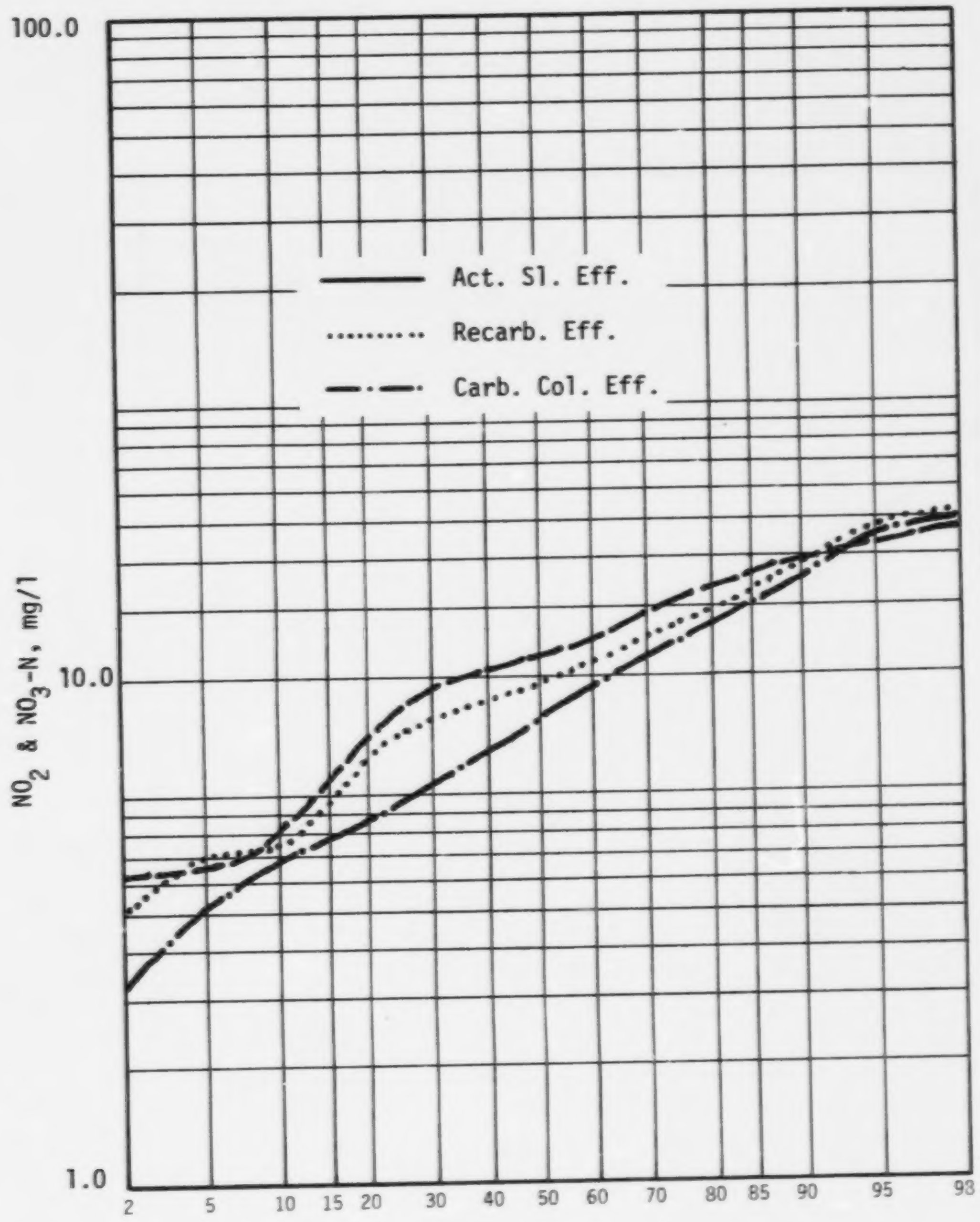

Figure 46. Frequency distributions for selected nitrate-nitrite nitrogen data; high-pH lime coagulation and recarbonation study.

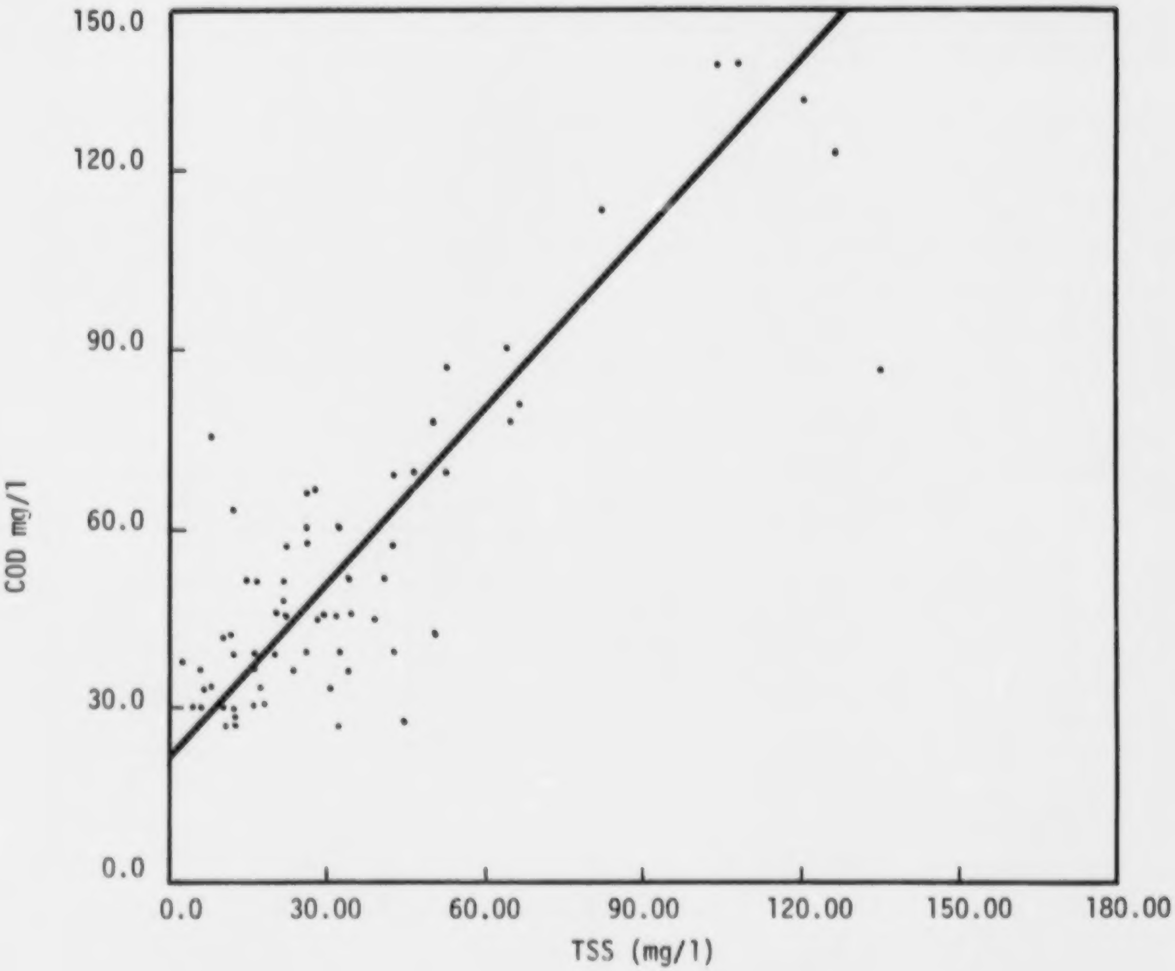

Figure 47. Plot of effluent COD versus effluent TSS for the CMAS system, high-pH lime coagulation and recarbonation study.

UPFLOW CLARIFIER

Table 39 summarizes the performance of the upflow clarifier (Infilco Densator), and Table 40 summarizes the operation of the process. During this phase of the research effort lime was fed as the primary coagulant, and 12 mg/l of ferric chloride (as $FeCl_3$) was fed as a flocculation aid.

The process performed about as anticipated, with notable exception of the very high effluent TSS concentration (75 mg/l). The effluent solids seemed to be unsettled floc, and the VSS concentration was always less than 5 mg/l which indicates that the upflow clarifier effectively captured the solids carryover from the activated sludge system.

The high effluent TSS concentrations can be attributed to a lime dose that was inadequate for obtaining proper coagulation/flocculation. The target pH value for operation of the up-flow clarifier was 11.3, since previous studies had indicated that excellent coagulation was obtained at that pH value. The average pH value of 10.5 produced an effluent that was poorly coagulated and very turbid. A lime shipment was received just prior to the start of this phase that had a CaO content of only 45 percent (76 percent was typical) and contained large quantities of grit. The lime fed poorly, and these difficulties resulted in consistent underfeeding.

Very significant reductions in bacterial densities were observed during this phase of the project as a result of the high-pH lime coagulation process. Even though the mean (arithmetic) pH of the Densator effluent was only 10.5 a total coliform reduction of almost five logs was observed.

SINGLE-STAGE RECARBONATION

The recarbonation basin was operated at an average flow of 3.2 liters/sec (50 gpm) which resulted in a theoretical residence time of 31 minutes. With an average CO_2 dose of 460 mg/l the basin performed reasonably well as the data in Table 41 indicate.

The major difficulty encountered in the operation of this process was the calcium carbonate scaling of the PVC piping used for the influent and scale build-up on the impeller of the effluent pump. This was a very major problem, even though the piping and pump were acid washed every three days with dilute HCl.

The reduction in TSS can be attributed to both resolubilization of $CaCO_3$ and settling. The settling of TSS in the basin made it necessary to remove sludge by bucket and rope about once a month.

No meaningful changes were observed in the gross organic water quality parameters or in the mean concentrations of the various forms of nitrogen. However, substantial changes were noted in the observed bacterial densities. Approximately a one and one-half log increase was observed for the standard plate counts and for coliform organisms.

TABLE 39. PERFORMANCE SUMMARY FOR THE UPFLOW CLARIFIER, HIGH-pH LIME COAGULATION AND RECARBONATION STUDY

Parameter	Activated Sludge Effluent (mg/l)	Densator Effluent (mg/l)	Reduction (percent)
COD	65	28	56.9
TOC, soluble	11	9	18.2
BOD_5	38	4	89.5
TSS	44	75	N/A
TDS	536	633	N/A
SC, μmho/cm	762	1084	N/A
NH_3 -N	1.90	2.70	N/A
Org. N	4.43	1.92	56.7
NO_2+NO_3 -N	9.9	10.7	N/A
NO_2 -N	0.053	0.096	N/A
Total P	7.4	1.3	82.4
pH units	7.1	10.5	N/A
T. Alk. as $CaCO_3$	129	204	N/A
P. Alk. as $CaCO_3$	0	130	N/A
Std. Plate Count per ml	9.3×10^3	18	99.8
Total Coliforms per 100 ml	3.2×10^5	8	99.997
Fecal Coliforms per 100 ml	2.5×10^4	6	99.98

N/A: Not Applicable

TABLE 40. PROCESS SUMMARY FOR THE UPFLOW CLARIFIER, HIGH-pH LIME COAGULATION AND RECARBONATION STUDY

Q (influent)	6.9 l/sec (110 gpm)
Q (recycle)	0.9 l/sec (14 gpm)
Q (waste)	8248 l/day (2179 gpd)
Mixing T	6.9 min.
G	67 $sec.^{-1}$
Settling T	3.5 hours
Clarifier overflow rate	31.9 m^3/day-m^2 (784 gal/ft^2-day)
Weir loading	35.8 m^3/day-m 2880 gal/ft-day)
Lime dose	279 mg/l
$FeCl_3$ dose	12 mg/l

TABLE 41. PERFORMANCE SUMMARY FOR THE RECARBONATION BASIN, HIGH-pH LIME COAGULATION AND RECARBONATION SYSTEM

Parameter	Densator Effluent (mg/l)	Recarb Effluent (mg/l)	Reduction (percent)
COD	28	27	3.6
TOC, Soluble	9	9	0.0
BOD_5	4	5	N/A
TSS	75	33	56.0
TDS	633	598	5.5
SC, µmho/cm	1084	919	15.2
NH_3 -N	2.70	2.36	12.6
Org. N	1.92	2.21	N/A
NO_2 +NO_3 -N	10.7	9.5	11.2
NO_2 -N	0.096	0.118	22.9
Total P	1.3	1.0	23.1
pH, units	10.5	7.0	N/A
T. Alk. as $CaCO_3$	204	221	N/A
P. Alk. as $CaCO_3$	130	12	N/A
Std. Plate Count per ml	18	2.3×10^3	N/A
Total Colifroms per 100 ml	8	2.3×10^2	N/A
Fecal Coliforms per 100 ml	6	1.7×10^2	N/A

N/A: Not Applicable

The increased bacterial populations were attributed to recontamination of the basin during those periods when the lime feed to the up-flow clarifier was interrupted. When this interruption occurred the pH in the Densator decreased to neutral values and large numbers of organisms passed to the recarbonation basin. When lime feed to the Densator was reestablished, the high-pH did not influence the microorganisms in the recarbonation basin since it was always operated at a neutral pH value.

MULTIMEDIA FILTER

The No. 1 multimedia filter (Neptune Microfloc media) was operated at an average flow of 1.8 liters/sec (29 gpm), which resulted in a filtration rate of 5.62 m/hr (2.3 gpm /ft^2). The filters were backwashed when the headloss was approximately 3 meters, and the average run time between backwashes was 74 hours. The backwash water consumption averaged 1.03 percent of the filter's effluent flow. The No. 1 filter performed very well during this portion of the project. Arithmetic means for the water quality data are presented in Table 42.

The TSS reduction of almost 85 percent resulted in low product water turbidity and an average TSS concentration in the filter effluent of 5 mg/l. It should be noted that filtration did not reduce the average total phosphorus concentration, indicating that the phosphorus was soluble. This problem resulted from the inadequate lime dose.

Only very slight reductions in the COD, soluble TOC, and BOD_5 concentrations were observed. The result was anticipated since virtually all of the solids in the effluent from the recarbonation basin were inorganic.

The specific conductance and the TDS concentration both increased slightly. The increase in total alkalinity suggests that solubilization of carbonates to bicarbonates is the most likely explanation for the TDS and specific conductance increases.

The geometric means for the observed microbiological parameters increased less than one log. This increase indicated that some bacterial growth was occurring within the filter, but no water quality changes of consequence appeared to have resulted from the growth.

ACTIVATED CARBON ADSORPTION

The activated carbon adsorption column was operated at an average flow of 101 liters/sec. (18 gpm) during the last phase of the project which resulted in a filtration (surface loading) rate of 2.32 m/hr (1.4 gpm/sq.ft.). The average run time between backwashes was 68 hours and the washwater consumption was 0.95 percent of the product water.

The empty-bed contact time of 52 minutes produced COD, TOC, and BOD_5 removals that were excellent as the data presented in Table 43 indicate. Figure 48 presents probability distributions for TOC data, and the difference in median soluble TOC concentrations in the activated sludge

TABLE 42. PERFORMANCE SUMMARY FOR THE NO. 1 MULTIMEDIA FILTER, HIGH-pH LIME COAGULATION AND RECARBONATION STUDY

Parameter	Recarb Effluent (mg/l)	Multimedia Filter Effluent (mg/l)	Reduction (percent)
COD	27	25	7.4
TOC, soluble	9	7	22.2
BOD_5	5	4	20.0
TSS	33	5	84.8
TDS	598	645	N/A
SC, µmho/cm	919	974	N/A
NH_3 -N	2.36	2.78	N/A
Org. N	2.21	2.15	2.7
NO_2+NO_3 -N	9.5	10.4	N/A
NO_2 -N	0.118	0.131	N/A
Total P	1.0	1.0	0
pH, units	7.0	6.6	N/A
T. Alk. as $CaCO_3$	221	230	N/A
P. Alk. as $CaCO_3$	12	0	N/A
Std. Plate Count per ml	2.3×10^3	1.9×10^4	N/A
Total Coliforms per 100 ml	2.3×10^2	9.4×10^2	N/A
Fecal Coliforms per 100 ml	1.7×10^2	2.9×10^2	N/A

N/A: Not Applicable

TABLE 43. PERFORMANCE SUMMARY FOR THE NO. 4 CARBON COLUMN, HIGH-pH LIME COAGULATION AND RECARBONATION

Parameter	Multimedia Filter Effluent (mg/l)	Carbon Column Effluent (mg/l)	Reduction (percent)
COD	25	8	68.0
TOC, soluble	7	3	57.1
BOD_5	4	2	50.0
TSS	5	4	20.0
TDS	645	637	1.2
SC, μmho/cm	974	981	N/A
NH_3 -N	2.78	2.73	1.8
Org. N	2.15	1.11	48.4
NO_2 +NO_3 -N	10.4	10.8	N/A
NO_2 -N	0.131	0.117	10.7
Total P	1.0	0.9	10.0
pH, units	6.6	6.8	N/A
T. Alk. as $CaCO_3$	230	236	N/A
P. Alk. as $CaCO_3$	0	0	0
Std. Plate Count per ml	1.9×10^4	3.3×10^3	82.6
Total Coliforms per 100 ml	9.4×10^2	1.3×10^2	86.2
Fecal Coliforms per 100 ml	2.9×10^2	59	79.7

N/A: Not Applicable

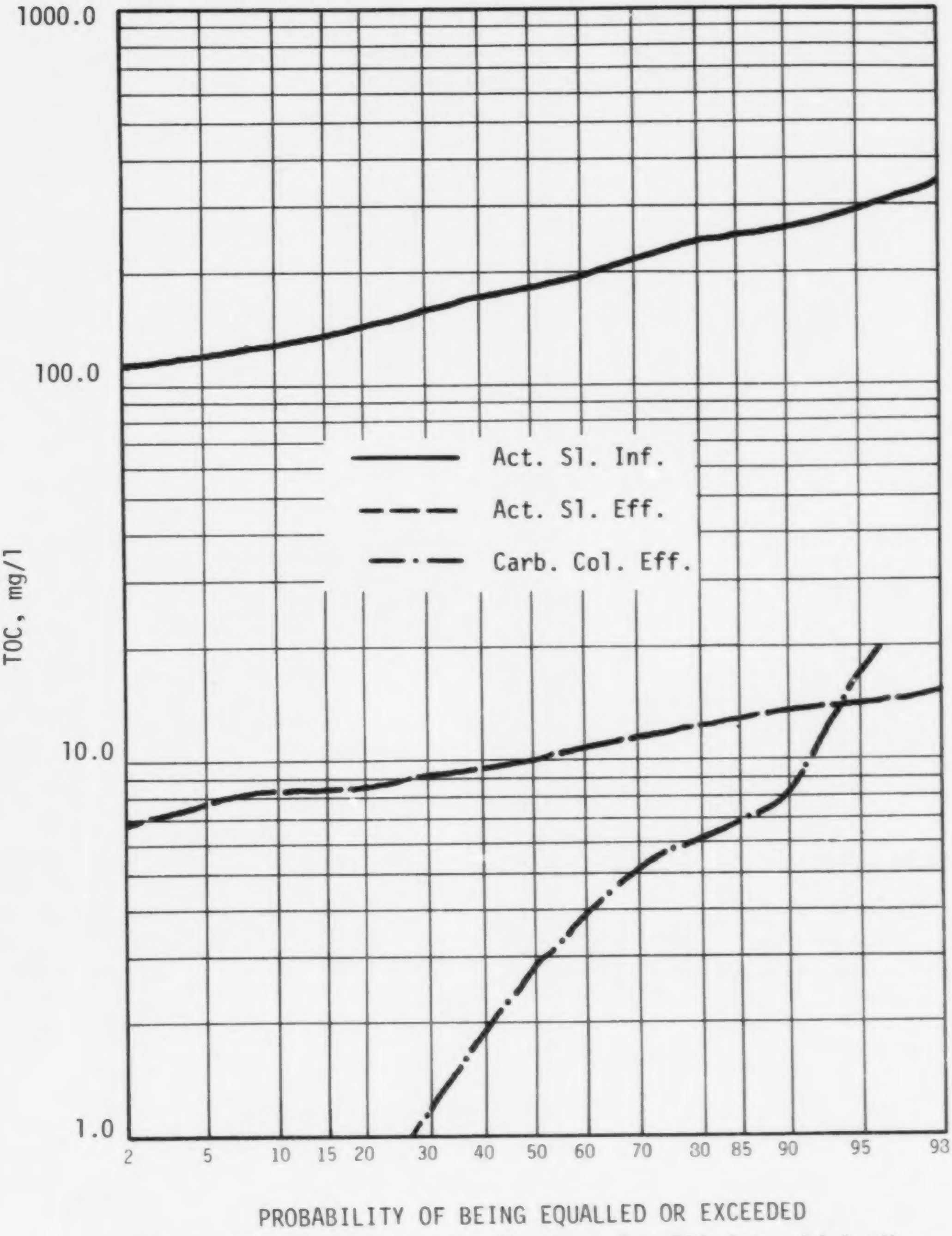

Figure 48. Frequency distributions for TOC data; high-pH lime coagulation and recarbonation study.

and activated carbon effluents is very evident. The ability of the carbon to remove color, and to a lesser extent organic nitrogen is shown in Figures 49 and 50, respectively.

Figure 51 shows probability distributions for total phosphorus concentrations, and indicates the capability of the AWT processes for removing phosphorus, although improved pH control and lime feed would have reduced the total phosphorus concentrations to even lower levels.

The half-log reductions observed in bacterial densities are probably not significant in terms of either process design or facility operations.

METALS REMOVALS

Summaries of the metals data for the high-pH lime coagulation and single-stage recarbonation phase of the research program are presented in Tables 44 through 49 in order of their location in the treatment sequence. For the purpose of studying metals removal the Densator and the recarbonation basin have been treated as a single chemical treatment process. Even though the metals data from the upflow clarifier are presented in Table 46, they were not used in statistical comparisons with the other two treatment sequences, instead the recarbonation basin effluent concentrations were used.

Aluminum

The mean and median removals of aluminum were 32 percent and 54 percent through the activated sludge unit, and 68 percent and 59 percent through the chemical treatment processes. The reductions in the latter exhibited a very strong correlation with the metal concentration (r=0.995), the optimum pH ranged between 10.0 to 10.5. Both multimedia filtration and carbon adsorption failed to reduce the average concentrations; however, the carbon column did significantly reduce the extreme values.

Arsenic

Very little removal of arsenic was observed across the biological treatment process, but high-pH lime clarification and recarbonation effected removals of 81 percent (mean) and 77 percent (median). The reductions exhibited a very strong concentration effect (r=0.99), but other correlations were not discovered.

Filtration further reduced the mean concentration by about 0.4 μg/l, and little or no removal occurred in the carbon column.

Mean and median train removals of arsenic were 84 percent and 79 percent, respectively. The EPA drinking water MCL of 0.05 mg/l was exceeded by 9 percent of the train influent samples and none of the train effluent samples.

The probability distributions shown in Figure 52 vividly illustrate

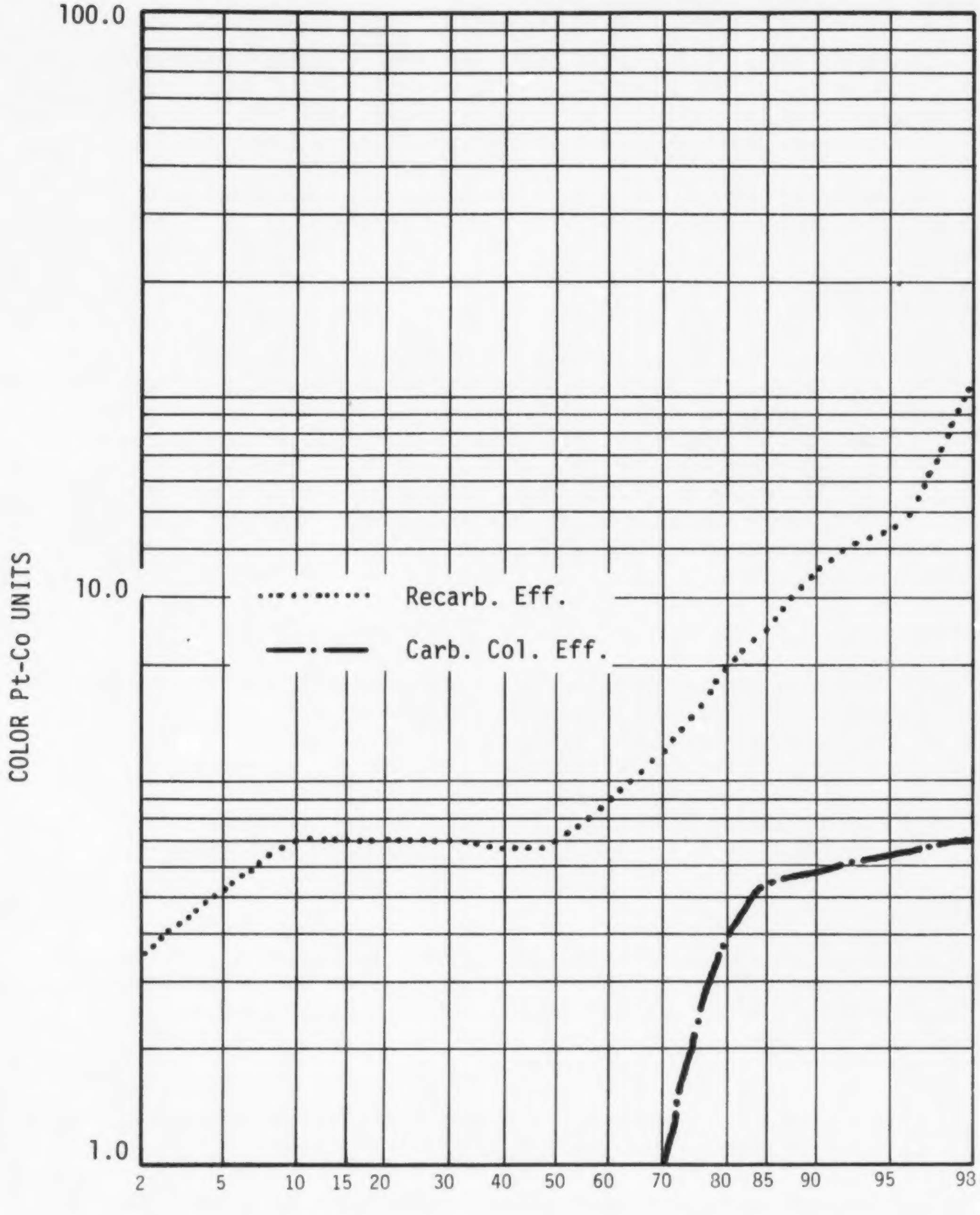

Figure 49. Frequency distributions for selected color data; high-pH lime coagulation and recarbonation study.

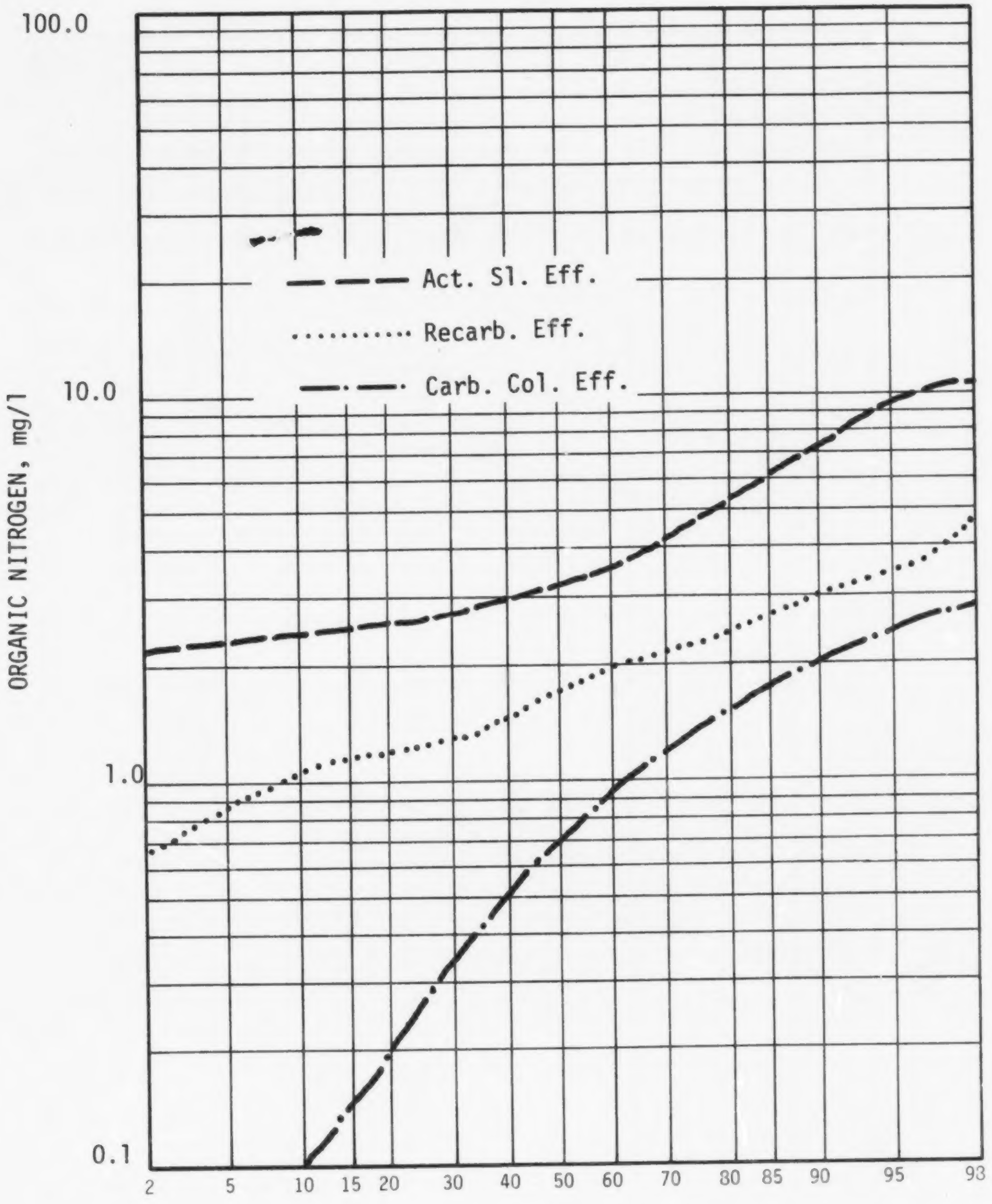

Figure 50. Frequency distributions for selected organic nitrogen data; high-pH lime coagulation and recarbonation study.

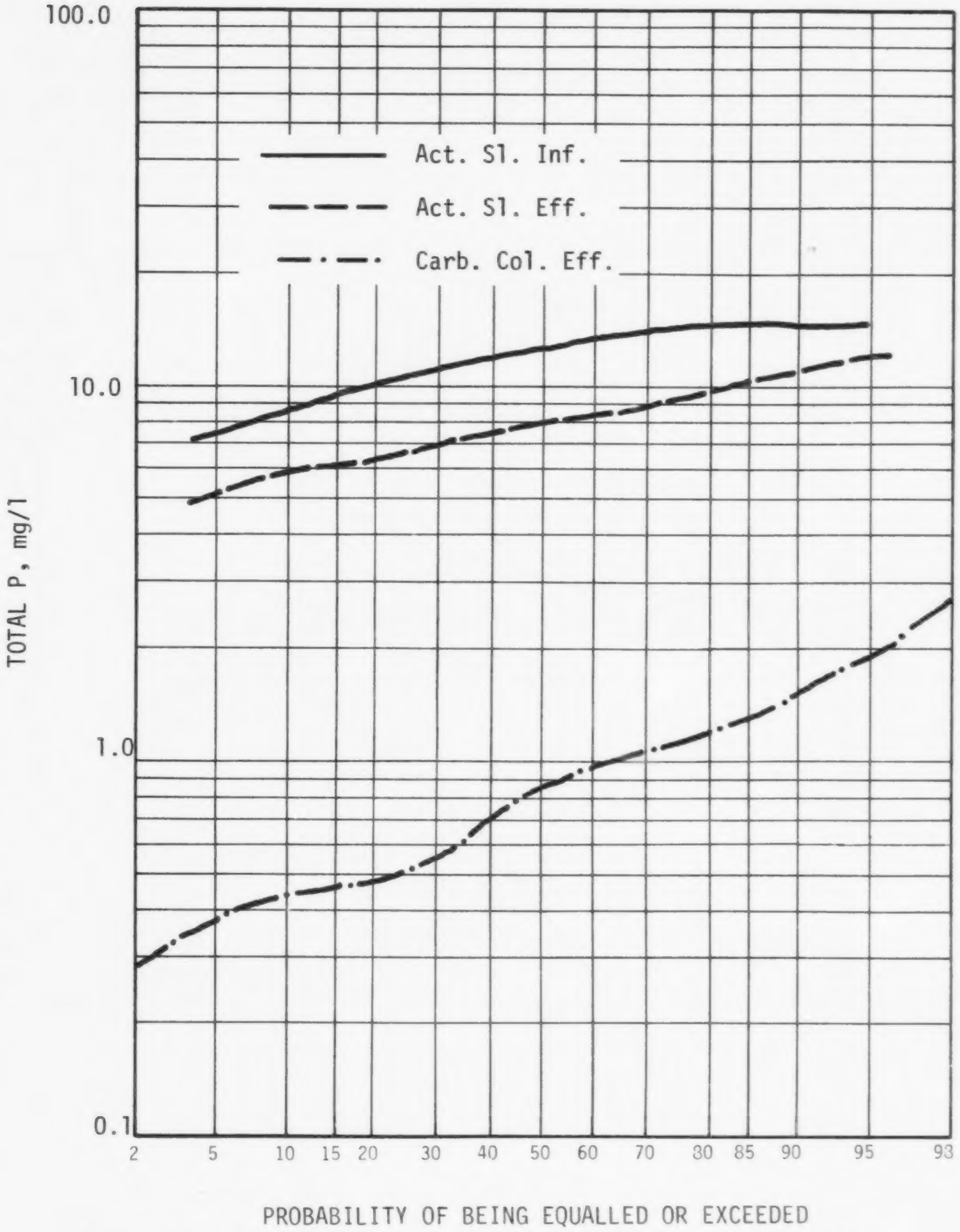

Figure 51. Frequency distributions for selected total P data; high-pH lime coagulation and recarbonation study.

TABLE 44. ACTIVATED SLUDGE INFLUENT METALS SUMMARY
HIGH-pH LIME TREATMENT WITH RECARBONATION
NOVEMBER 1973 - JANUARY 1974

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Al	0.64	0.64	0.69	0.28	1.60	0.25	41
As*	13.5	15.0	21.2	22.9	119.0	2.3	45
B	0.35	0.35	0.36	0.097	0.65	0.16	42
Ba	0.110	0.105	0.115	0.042	0.25	0.01	45
Ca	64.5	64.2	66.2	18.1	144.0	32.0	44
Cd*	11.5	12.6	13.7	7.9	38.0	2.0	46
Co	0.051	0.050	0.052	0.014	0.081	0.028	44
Cr	0.090	0.094	0.114	0.090	0.620	0.015	46
Cu	0.121	0.137	0.182	0.156	0.820	0.021	44
Fe	0.80	0.79	0.85	0.32	1.63	0.37	44
Hg*	0.26	0.25	0.28	0.16	0.75	0.0	38
Mg	5.25	5.00	5.14	1.05	7.33	1.62	43
Mn	0.079	0.077	0.079	0.016	0.110	0.043	44
Na	96.5	90.9	93.8	21.7	127.0	33.0	44
Ni	0.126	0.119	0.136	0.068	0.310	0.015	44
Pb	0.080	0.082	0.089	0.035	0.20	0.02	45
Se*	3.8	4.3	7.8	8.4	33.0	0.0	26
Si	9.4	9.4	9.7	2.4	17.0	3.9	41
Sr	0.88	0.71	0.79	0.32	1.25	0.23	41
V*	3.1	3.1	3.4	1.3	8.5	0.5	32
Zn	0.180	0.184	0.203	0.098	0.60	0.08	44

Concentration in mg/l (*μg/l)

TABLE 45. ACTIVATED SLUDGE EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITH RECARBONATION NOVEMEBER 1973 - JANUARY 1974

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Al	0.30	0.33	0.47	0.61	3.5	0.02	42
As*	13.4	15.6	20.6	18.0	85.0	2.4	47
B	0.35	0.36	0.36	0.074	0.56	0.25	43
Ba	0.070	0.067	0.075	0.034	0.24	0.005	46
Ca	65.0	63.1	64.9	16.2	118.0	39.0	45
Cd*	6.0	6.0	7.3	4.1	23.0	1.0	47
Co	0.048	0.046	0.048	0.013	0.073	0.020	45
Cr	0.044	0.041	0.052	0.044	0.270	0.002	47
Cu	0.055	0.065	0.077	0.052	0.290	0.012	45
Fe	0.50	0.73	1.45	2.68	14.90	0.10	45
Hg*	0.17	0.19	0.26	0.25	1.075	0.05	39
Mg	5.05	4.91	4.96	0.64	5.94	3.21	44
Mn	0.060	0.053	0.066	0.046	0.250	0.003	45
Na	94.0	88.0	90.3	19.6	127.0	45.0	45
Ni	0.103	0.101	0.106	0.036	0.20	0.044	45
Pb	0.04	0.043	0.050	0.034	0.17	0.01	46
Se*	2.2	2.2	2.4	2.2	8.8	0.0	28
Si	9.4	9.0	9.3	2.2	13.5	4.6	42
Sr	0.83	0.63	0.72	0.30	1.19	0.16	42
V*	2.8	2.7	2.9	1.1	8.0	1.3	34
Zn	0.090	0.110	0.133	0.097	0.48	0.05	45

Concentration in mg/l (* μg/l)

TABLE 45. UP-FLOW CLARIFIER EFFLUENT METALS SUMMARY
HIGH-pH LIME TREATMENT WITH RECARBONATION
NOVEMBER 1973 - JANUARY 1974

	MEDIAN	GEO-MEAN	ARITH-MEAN	σ	MAX.	MIN.	N
Al	0.15	0.16	0.18	0.12	0.55	0.02	40
As*	3.9	3.3	5.6	7.4	46.5	0.0	44
B	0.37	0.37	0.38	0.09	0.64	0.22	42
Ba	0.085	0.078	0.086	0.032	0.140	0.010	44
Ca	103.0	101.2	105.4	29.6	172.0	49.0	43
Cd*	4.0	3.0	3.6	1.3	6.0	1.0	45
Co	0.064	0.063	0.067	0.023	0.116	0.019	43
Cr	0.009	0.011	0.014	0.018	0.120	0.003	45
Cu	0.047	0.0045	0.050	0.026	0.140	0.019	43
Fe	0.56	0.54	0.97	2.42	16.3	0.09	43
Hg*	0.10	0.11	0.11	0.10	0.40	0.0	39
Mg	2.71	2.20	2.58	1.28	5.56	0.56	42
Mn	0.015	0.015	0.019	0.016	0.102	0.002	43
Na	94.0	88.4	90.5	18.9	121.0	49.0	43
Ni	0.084	0.079	0.087	0.039	0.200	0.030	43
Pb	0.030	0.028	0.029	0.010	0.06	0.01	44
Se*	0.5	1.4	1.4	2.0	7.3	0.0	28
Si	7.9	8.2	8.7	3.2	20.0	3.7	40
Sr	0.68	0.59	0.66	0.26	1.11	0.15	40
V*	3.3	3.2	3.4	1.0	6.2	1.6	34
Zn	0.040	0.052	0.084	0.110	0.58	0.01	43

Concentration in mg/l (*µg/l)

TABLE 47. RECARBONATION BASIN EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITH RECARBONATION NOVEMBER 1973 - JANUARY 1974

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Al	0.12	0.13	0.15	0.09	0.43	0.03	38
As*	3.1	3.2	3.9	3.0	15.3	0.0	40
B	0.35	0.34	0.34	0.07	0.49	0.20	38
Ba	0.090	0.080	0.084	0.032	0.15	0.0	41
Ca	98.0	100.6	106.1	34.1	180.0	39.0	41
Cd*	3.0	3.1	3.4	1.4	7.0	1.0	41
Co	0.065	0.063	0.067	0.023	0.115	0.022	41
Cr	0.008	0.009	0.011	0.009	0.050	0.004	41
Cu	0.050	0.053	0.073	0.069	0.33	0.013	41
Fe	0.51	0.46	0.82	1.77	11.50	0.04	41
Hg*	0.08	0.15	0.17	0.27	1.48	0.0	36
Mg	2.50	2.10	2.40	1.10	4.71	0.53	41
Mn	0.014	0.014	0.016	0.011	0.073	0.004	41
Na	94.0	87.1	90.0	20.9	120.0	34.0	41
Ni	0.082	0.076	0.083	0.032	0.160	0.030	41
Pb	0.030	0.026	0.027	0.007	0.04	0.01	40
Se*	1.0	0.1	1.5	1.8	5.8	0.0	26
Si	7.9	7.8	8.1	2.3	12.2	3.4	38
Sr	0.66	0.572	0.64	0.27	1.16	0.15	39
V*	3.2	3.1	3.2	0.6	4.8	1.5	32
Zn	0.430	0.355	0.654	0.864	4.10	0.02	41

Concentration in mg/l (*μg/l)

TABLE 48. FILTER EFFLUENT METALS SUMMARY HIGH-pH LIME TREATMENT WITH RECARBONATION NOVEMBER 1973 - JANUARY 1974

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Al	0.15	0.16	0.21	0.19	1.01	0.02	33
As*	3.0	2.3	3.5	3.5	19.3	0.0	33
B	0.35	0.35	0.36	0.08	0.57	0.19	31
Ba	0.090	0.090	0.094	0.028	0.15	0.03	33
Ca	85.0	91.4	96.5	33.4	171.0	54.0	33
Cd*	3.0	3.0	3.3	1.4	6.0	0.0	33
Co	0.059	0.057	0.062	0.022	0.108	0.016	33
Cr	0.007	0.007	0.008	0.004	0.027	0.003	33
Cu	0.059	0.063	0.082	0.092	0.560	0.026	33
Fe	0.21	0.21	0.24	0.17	1.00	0.07	33
Hg*	0.08	0.11	0.12	0.16	0.63	0.0	32
Mg	2.66	2.27	2.61	1.25	5.38	0.55	33
Mn	0.15	0.015	0.017	0.010	0.047	0.002	33
Na	80.0	78.9	82.5	23.3	118.0	36.0	33
Ni	0.068	0.065	0.072	0.029	0.150	0.010	33
Pb	0.030	0.025	0.026	0.006	0.03	0.01	33
Se*	1.3	1.7	1.7	2.5	11.0	0.0	20
Si	7.8	7.2	7.6	2.4	11.1	2.3	33
Sr	0.64	0.59	0.66	0.26	1.12	0.11	33
V*	3.5	3.5	3.6	0.8	4.9	1.2	27
Zn	0.390	0.375	0.532	0.503	2.60	0.04	33

Concentration in mg/l (*μg/l)

TABLE 49. CARBON COLUMN EFFLUENT METALS SUMMARY
HIGH-pH LIME TREATMENT WITH RECARBONATION
NOVEMEBER 1973 - JANUARY 1974

	MEDIAN	GEO. MEAN	ARITH. MEAN	σ	MAX.	MIN.	N
Al	0.16	0.14	0.16	0.08	0.31	0.03	33
As*	2.8	2.3	3.5	3.2	17.7	0.0	33
B	0.25	0.26	0.32	0.22	1.06	0.08	31
Ba	0.080	0.078	0.086	0.031	0.16	0.01	33
Ca	94.0	94.9	101.2	38.4	207.0	55.0	33
Cd*	3.0	3.0	3.0	1.4	8.0	0.0	33
Co	0.059	0.058	0.063	0.022	0.109	0.020	33
Cr	0.005	0.005	0.006	0.003	0.011	0.001	33
Cu	0.040	0.044	0.054	0.037	0.150	0.014	33
Fe	0.20	0.18	0.20	0.07	0.42	0.08	33
Hg*	0.03	0.10	0.08	0.13	0.60	0.0	32
Mg	2.37	2.19	2.46	1.13	5.26	0.53	33
Mn	0.016	0.014	0.017	0.009	0.045	0.002	33
Na	79.0	79.0	81.7	20.1	113.0	44.0	33
Ni	0.072	0.068	0.078	0.046	0.260	0.026	33
Pb	0.030	0.020	0.027	0.008	0.05	0.02	33
Se*	0.0	1.2	0.7	1.0	3.0	0.0	21
Si	7.8	7.1	7.3	1.9	11.0	3.9	33
Sr	0.65	0.59	0.64	0.24	1.15	0.09	33
V*	2.2	2.0	2.0	1.0	4.0	0.0	27
Zn	0.450	0.426	0.617	0.541	2.20	0.03	33

Concentration in mg/l (*µg/l)

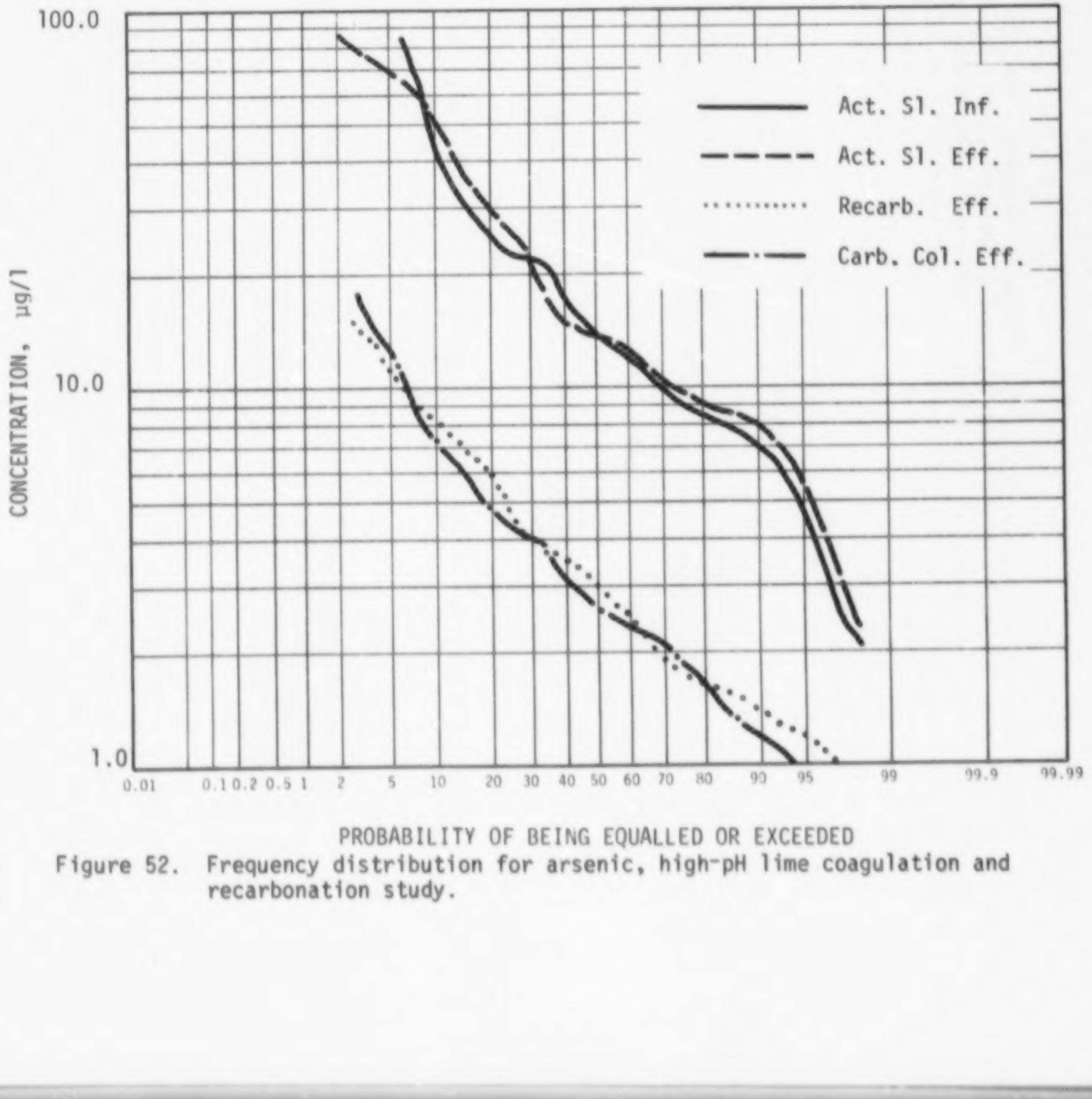

Figure 52. Frequency distribution for arsenic, high-pH lime coagulation and recarbonation study.

that the only process that was effective in removing arsenic was chemical treatment (high-pH coagulation and recarbonation); biological treatment, filtration, and carbon adsorption were virtually ineffective in reducing arsenic concentrations.

Boron

Boron was a refractory element in the treatment sequence. Only in the carbon column was there significant removal, 11 percent (mean) to 29 percent (median). The reductions through the carbon were proportional to the influent concentrations (r=0.32), and inversely proportional to X/M (r=0.24). In the latter case, the initial removals were in the range of 70-80 percent on virgin carbon, decreasing to 0-15 percent at X/M's of 0.06 and greater. The frequency distributions of boron in all of the effluents sampled were log-normal and near-identical, except for the carbon column effluent which had a bimodal distribution.

Barium

Barium was significantly removed in only the activated sludge process; the reductions were 35 percent (mean) and 36 percent (median). A mean increase of about 0.010 mg/l occurred during chemical treatment and the probable cause was contamination in the commercial lime. Little change in barium concentrations occurred through multimedia and carbon filtration, although in its virgin state, the carbon reduced the concentration of barium by 40-60 percent, declining to zero as the X/M approached about 0.10. None of the samples ever reached or exceeded the EPA drinking water MCL of 1.0 mg/l.

Frequency distributions for barium concentrations in the activated sludge influent and the product water are shown in Figure 53.

Calcium

The activated sludge process reduced the mean calcium concentration about 2 percent but a mean increase of 40.5 mg/l occurred in the Densator. There was no removal during the single-stage recarbonation process, as much of the calcium was converted directly to the soluble bicarbonate form.

Filtration removed about 9.6 mg/l of calcium, which resulted in a 9-percent reduction in the mean concentration. There was also some degree of correlation between effluent calcium and TSS. The mean and median increases in calcium through the train were 35 mg/l and 30 mg/l, respectively, the maximum observed train effluent concentration was 207 mg/l.

Cadmium

Cadmium was removed both by biological treatment, 47 percent by means and 48 percent by medians; and by chemical treatment, 53 percent (means) and 50 percent (medians). The reductions observed through the

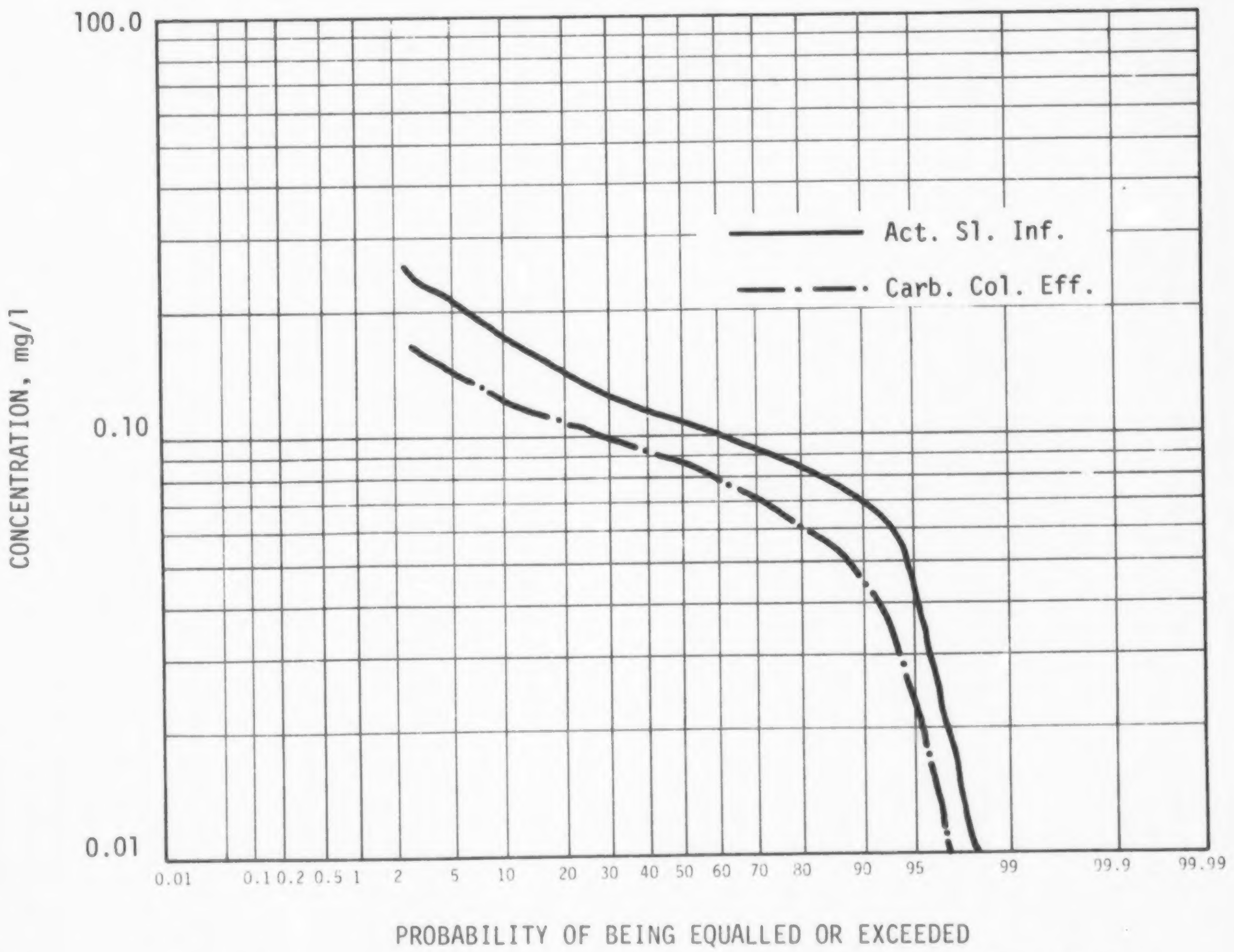

Figure 53. Frequency distributions for barium, high-pH lime coagulation and recarbonation study.

Densator and recarbonation basin exhibited a strong concentration effect (r=0.94). Negligible cadmium removals were observed through multimedia filtration and carbon adsorption. Fifty-six percent of the train influent samples contained cadmium in excess of the NIPDWR MCL of 0.01 mg/l; however, none of the product water samples exceeded the MCL.

The frequency distributions for cadmium concentrations in Figure 54 show rather clearly how effectively the biological and chemical processes removed cadmium.

Cobalt

The frequency distributions shown in Figure 55 indicate that cobalt was not removed in the high-pH lime with recarbonation train, due to its refractory nature and the fact that both the lime and ferric chloride coagulants contained trace quantities of the element. Chemical analysis revealed a cobalt content of 20 mg/l in the lime slurry and 19 mg/l in the ferric chloride solution. Based on applied chemical doses, it appears that more cobalt was derived from the lime feed than the ferric chloride; however, the calculated cobalt increase based on these analyses was only about 40 percent of the observed mean increase. There was not, as expected, a reasonably good correlation between the increase in cobalt and the chemical dose. Also, there was more than three times as much variation in the cobalt increases as in the chemical feed rates. The mean and median increases in cobalt through the treatment train were only 0.011 mg/l and 0.008 mg/l, respectively.

Chromium

Chromium was removed progressively to a lesser degree by each process in the treatment sequence. Mean and median removals were 54 percent and 51 percent by activated sludge, 79 percent and 82 percent by chemical treatment. Reductions through the Densator exhibited a very strong correlation with concentration (r=0.98), but there was not enough variation in the operating and process control parameters to evaluate their influence on chromium removed.

Further removals of 25 percent (means) and 13 percent (medians) were observed through multimedia filtration, and the reductions exhibited a concentration correlation (r=0.78). There was a linear relationship between filter effluent turbidity and chromium concentration (r=0.23). Carbon adsorption removed 33 percent (mean) and 29 percent (median), and very effectively damped extreme values. The reductions through the carbon column exhibited a strong correlation with concentration (r=0.83), and chromium removal appeared to decrease substantially when the effluent COD's exceeded about 15 mg/l. Ninety-one percent of the train influent samples contained chromium in excess of the EPA drinking water MCL of 0.05 mg/l, while none of the train effluent samples even approached this high a concentration.

Frequency distributions for chromium concentrations are shown in Figure 56.

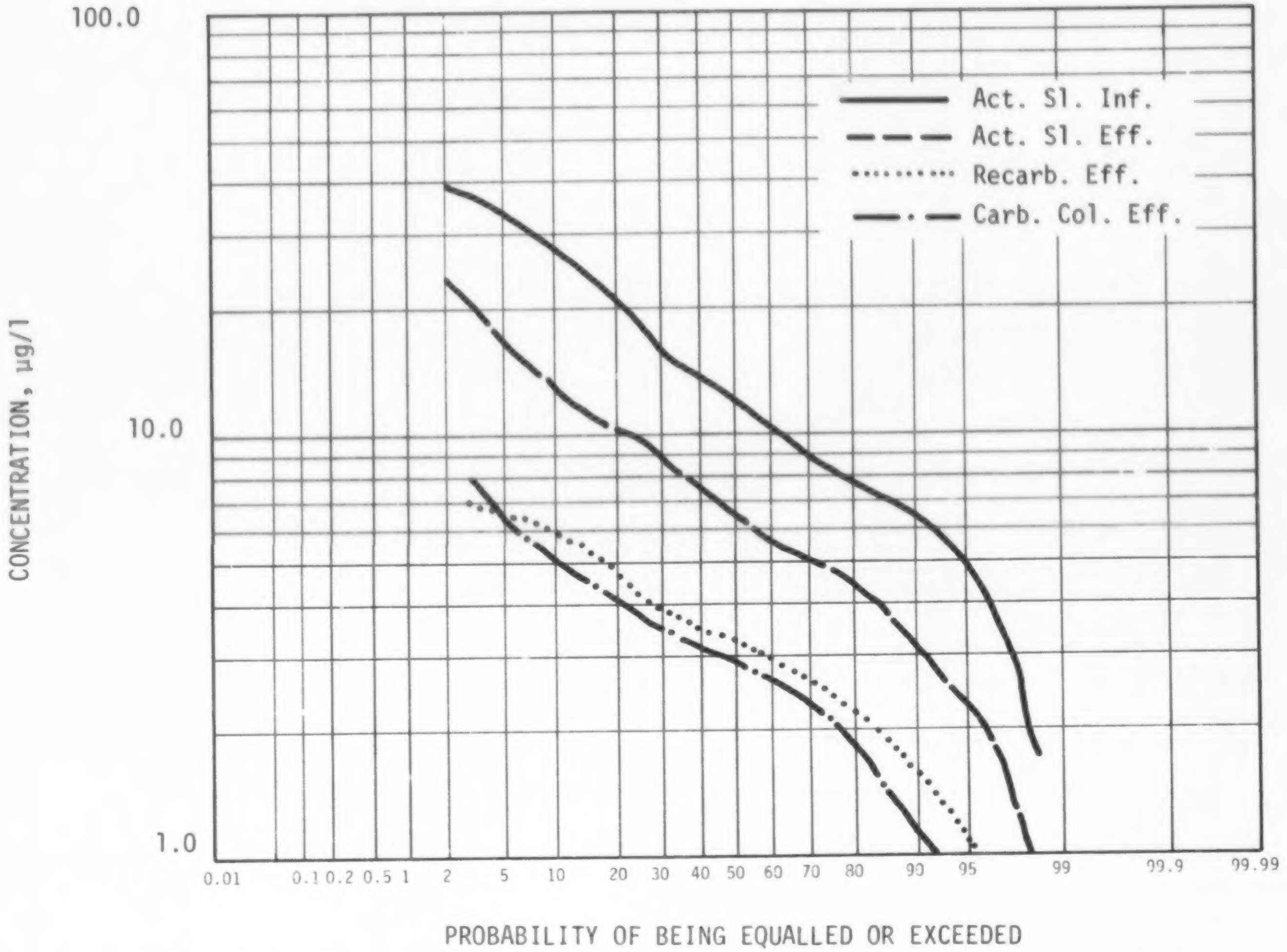

Figure 54. Frequency distributions for cadmium, high-pH lime coagulation and recarbonation study.

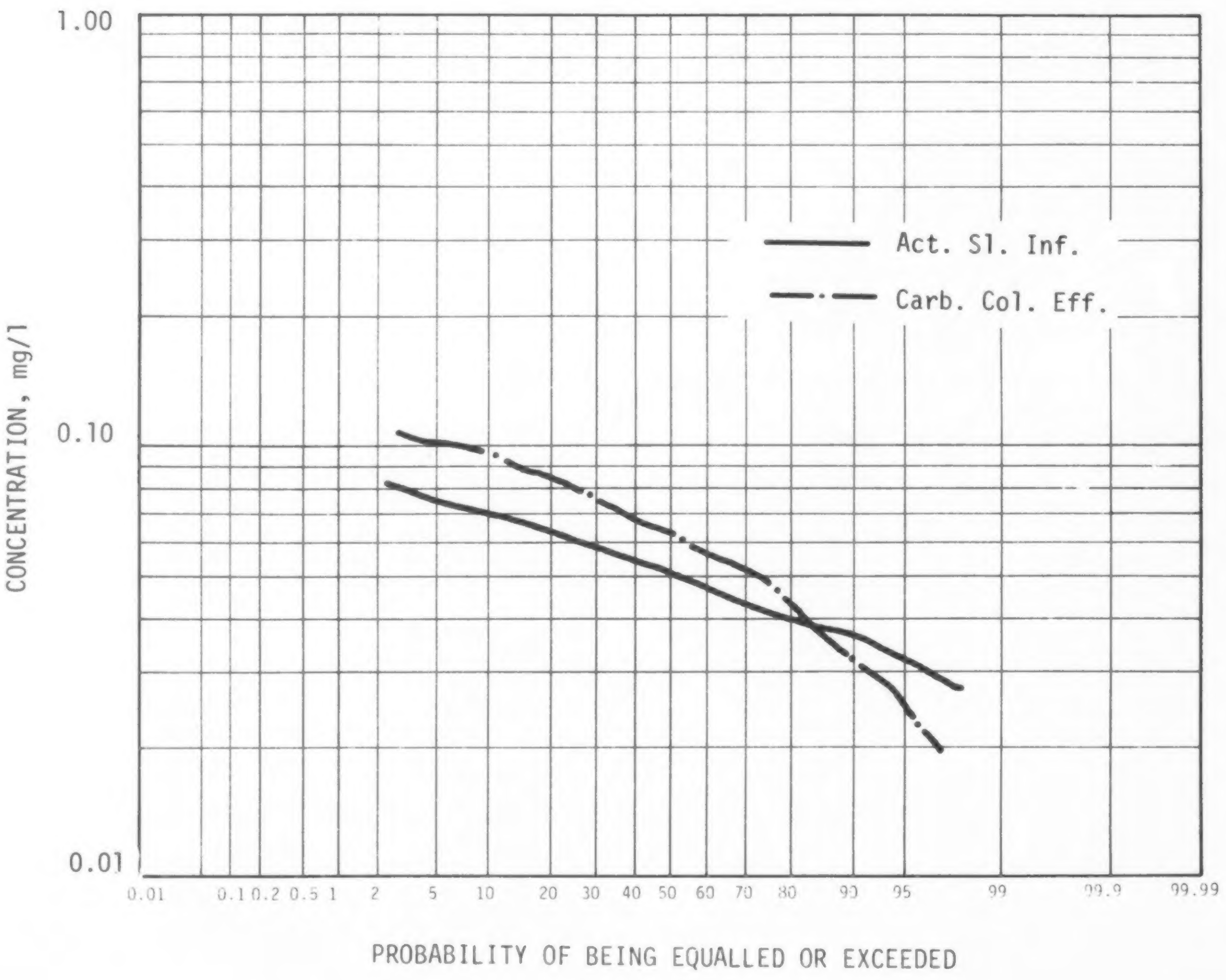

Figure 55. Frequency distributions for cobalt, high-pH lime coagulation and recarbonation study.

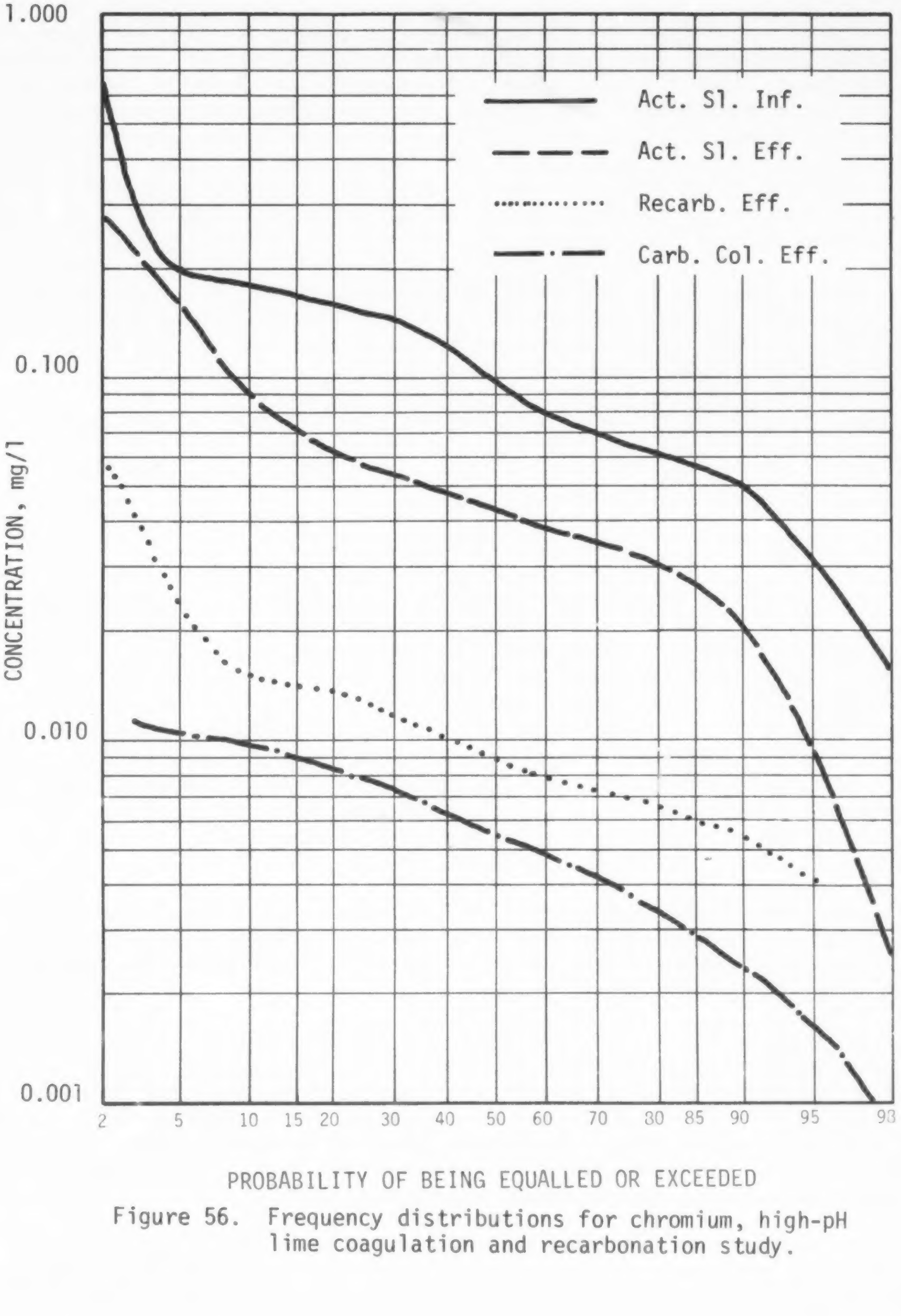

Figure 56. Frequency distributions for chromium, high-pH lime coagulation and recarbonation study.

Copper

Copper was removed during biological treatment and high-pH lime clarification, with mean and median removals of 58 percent and 54 percent in the former, and 35 percent and 15 percent in the latter. The removal of copper in the Densator exhibited a weak concentration correlation (r=0.58). However, there were sustained increases in the mean concentration through the recarbonation basin and multimedia filter of 0.023 mg/l and 0.009 mg/l respectively. The source of the increase through recarbonation was attributed to brass valves and miscellaneous fittings in the basin and on the influent line.

Copper removals by the activated carbon amounted to 34 percent (mean) to 32 percent (median). Reductions in concentration through the column exhibited a strong concentration correlation (r=0.93), but failed to correlate with NH_3N. Overall, there was a net removal of 71 percent (mean) and 67 percent (median) through the treatment sequence. In spite of the increases in the recarbonation basin and filter, the maximum observed concentration of 0.82 mg/l was found on the train influent; therefore, all samples were consistently well below the Secondary Regulation recommendation of 1.0 mg/l.

Iron

Analysis of iron was complicated by the occurrence of extreme values at all sample sites except the train influent and train effluent. Ferric chloride was metered into the aeration basin from January 4-31, 1974 in order to promote better settling in the secondary clarifier, where uncontrolled denitrification was causing a serious rising sludge problem. On 40 percent of the paired samples there was an increase in iron through the activated sludge unit, resulting in a mean negative removal (or addition) of 71 percent. At the same time, the median concentration decreased 37 percent. On three occasions the $FeCl_3$ feed rate was far in excess of the required dose, which provided an opportunity to study the removal of slug doses of iron through the remainder of train.

When ferric chloride was fed to the Densator as a flocculation aid, there was a mean average removal of 43 percent through high-pH coagulation and recarbonation. The reductions exhibiting a strong concentration correlation (r=0.85).

Multimedia filtration removed an additional 71 percent (mean) or 59 percent (median), and the reductions exhibited a very strong concentration correlation (r=0.997). The filter effluent TSS concentration was also a fair estimator of the iron concentration (r=0.40). Carbon filtration removed a final 18 percent (mean) or 5 percent (median), eliminating all extreme values. The reductions through carbon exhibited a reasonably strong concentration effect (r=0.90).

Through the entire treatment train there was a mean iron removal of 77 percent, and a median removal of 75 percent. All of the train influent samples exceeded 0.3 mg/l, the Secondary Regulation recommendation, compared to 6 percent of the train effluent samples. Both the train influent and effluent probability distributions had similar log-normal patterns, and were devoid of extreme values.

Mercury

Mean and median removals of mercury were 6 percent and 35 percent through biological treatment, 35 percent and 53 percent through chemical treatment. The reductions in the latter case exhibited a very weak correlation with concentration (r=0.31), and the Densator effluent mercury concentration was proportional to the total P concentration (r=0.44).

There was little change in the observed mercury concentrations as a result of multimedia filtration, but a median removal of 63 percent was observed through activated carbon. Reductions in mercury through the carbon column correlated with concentration (r=0.53); also, a linear correlation between effluent mercury and COD (r=0.53) was noted. The train removals for mercury were 71 percent (mean) and 89 percent (median). All samples were well below the EPA drinking water MCL of 0.002 mg/l.

Frequency distributions are shown for mercury concentrations in Figure 57.

Magnesium

Only an average of 0.2 mg/l of magnesium was removed during biological treatment compared to approximately 2.6 mg/l removed during chemical treatment. The chemical treatment processes produced magnesium removals of 52 percent (mean) or 50 percent (median). Because the average pH established in the Densator was less than that required for complete magnesium removal, approximately 2.5 mg/l remained in the effluent. There were, however, a few days when the pH was sufficiently high to effect removals up to 90 percent, which provided an opportunity to study the pH-alkalinity relationships on magnesium removal. The effluent magnesium concentration was inversely proportional to methyl orange alkalinity (r=0.65), phenolphthalein alkalinity (r=0.66), pH (r= 0.40), and directly proportional to turbidity (r=0.86) and total P (r=0.34).

Multimedia filtration failed to remove magnesium. There was, in fact, a slight increase in magnesium across the filter, due probably to floc breakup. The effluent magnesium concentration was directly proportional to TSS (r=0.31) and turbidity (r=0.53). Carbon adsorption reduced magnesium concentrations 6 percent (mean) to 11 percent (median); the reductions exhibited a concentration correlation (r=0.53). The distribution of concentrations in all process streams was clearly bimodal.

Manganese

Biological removal of manganese averaged only 17 percent (mean) or 24 percent (median), contrasted with mean and median removals of 76 percent and 77 percent through the chemical treatment processes. The

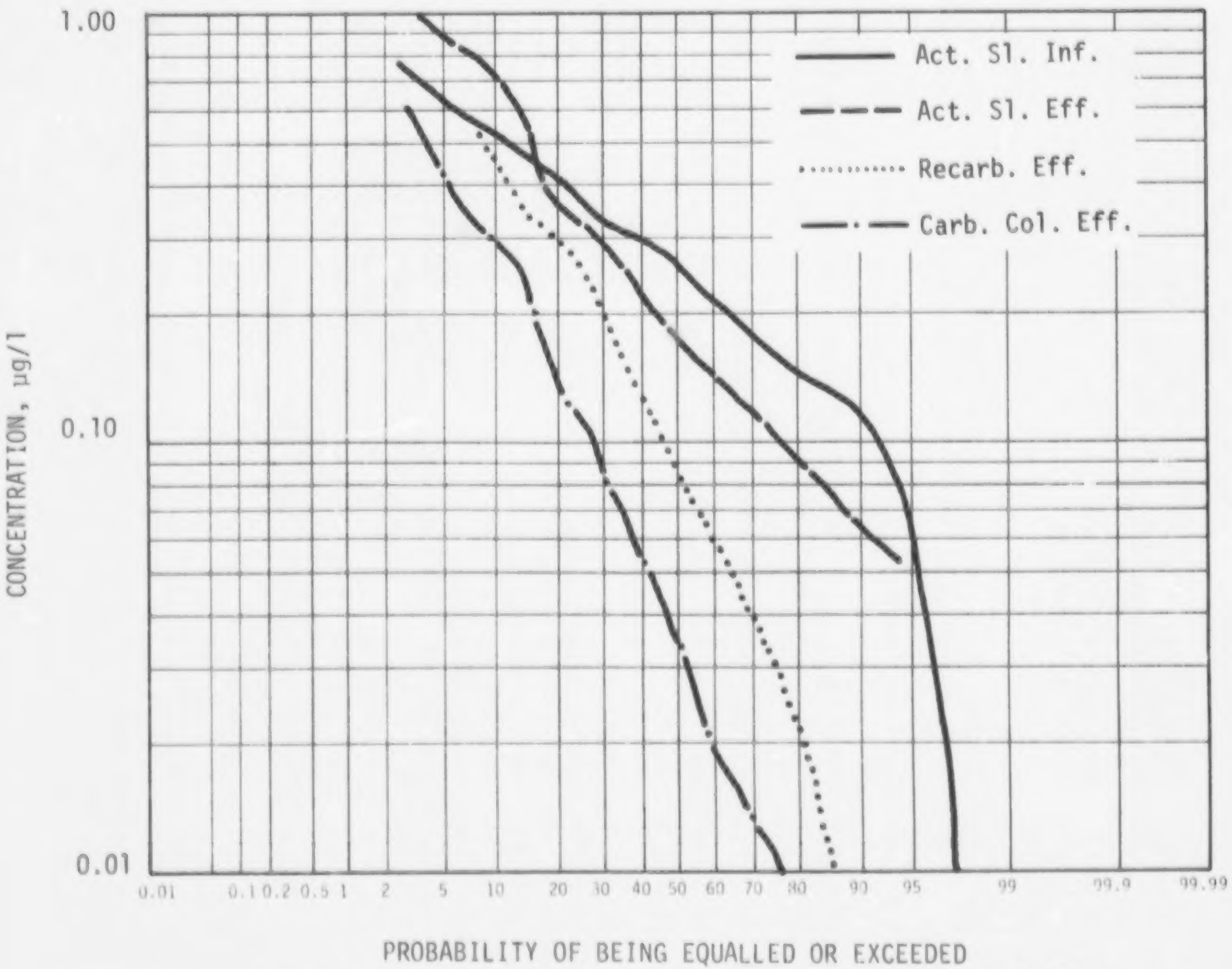

Figure 57. Frequency distributions for mercury, high-pH lime coagulation and recarbonation study.

reductions through the Densator exhibited a strong concentration correlation (r=0.97); the reductions declined slightly with increasing effluent TSS and total P. Little or no removal occurred through multimedia filtration or carbon adsorption. The Secondary Regulations recommended drinking water limit of 0.05 mg/l was exceeded in 95 percent of the train influent samples, and none of the train effluent samples.

Sodium

Sodium was refractory with the exception of a slight, and unexplained, removal of 8 percent (mean) to 15 percent (median) during multimedia filtration. There was no significant contamination of the treatment train arising from the addition of chemicals. Upon analysis, the ferric chloride slurry contained about 310 mg/l Na, which would represent a calculated increase of only 0.006 mg/l in the Densator. Since the observed increase was higher, the lime may have also contained trace amounts of sodium, but not enough to impart more than about 0.2 mg/l (the observed increase) into the water. Overall removals were 13 percent (means) and 18 percent (medians), the maximum train effluent concentration being 113 mg/l.

Nickel

Mean and median removals of nickel during biological treatment averaged 22 percent and 18 percent, respectively. Removals through chemical treatment averaged 22 percent (mean) or 20 percent (median), and decreased slightly with increasing effluent TSS and total P. The reductions exhibited a slight linear concentration effect (r=0.52). No correlations in nickel removal were observed as a result of the multimedia filtration, where the mean and median removals averaged 13 percent and 17 percent, respectively. Nickel was not removed by carbon. Both the mean and median train removals averaged 43 percent.

Probability distributions for nickel concentrations are given in Figure 58.

Lead

Those data used to develop the probability distributions shown in Figure 59 indicate that most of the lead was removed during biological treatment, the mean and median removal efficiencies were 22 percent and 18 percent, respectively. Removals through chemical treatment averaged 45 percent (mean) and 25 percent (median), the only good correlation being a concentration effect on lead reductions (r=0.98). There was essentially no change in the lead concentration as a result of filtration and carbon adsorption. The train effluent mean and median concentrations were both approximately 0.03 mg/l. Although the train removals were not great, approximately 82 percent of the train influent samples violated the EPA drinking water MCL of 0.05 mg/l, while none of the train effluent samples exceeded the limit.

Selenium

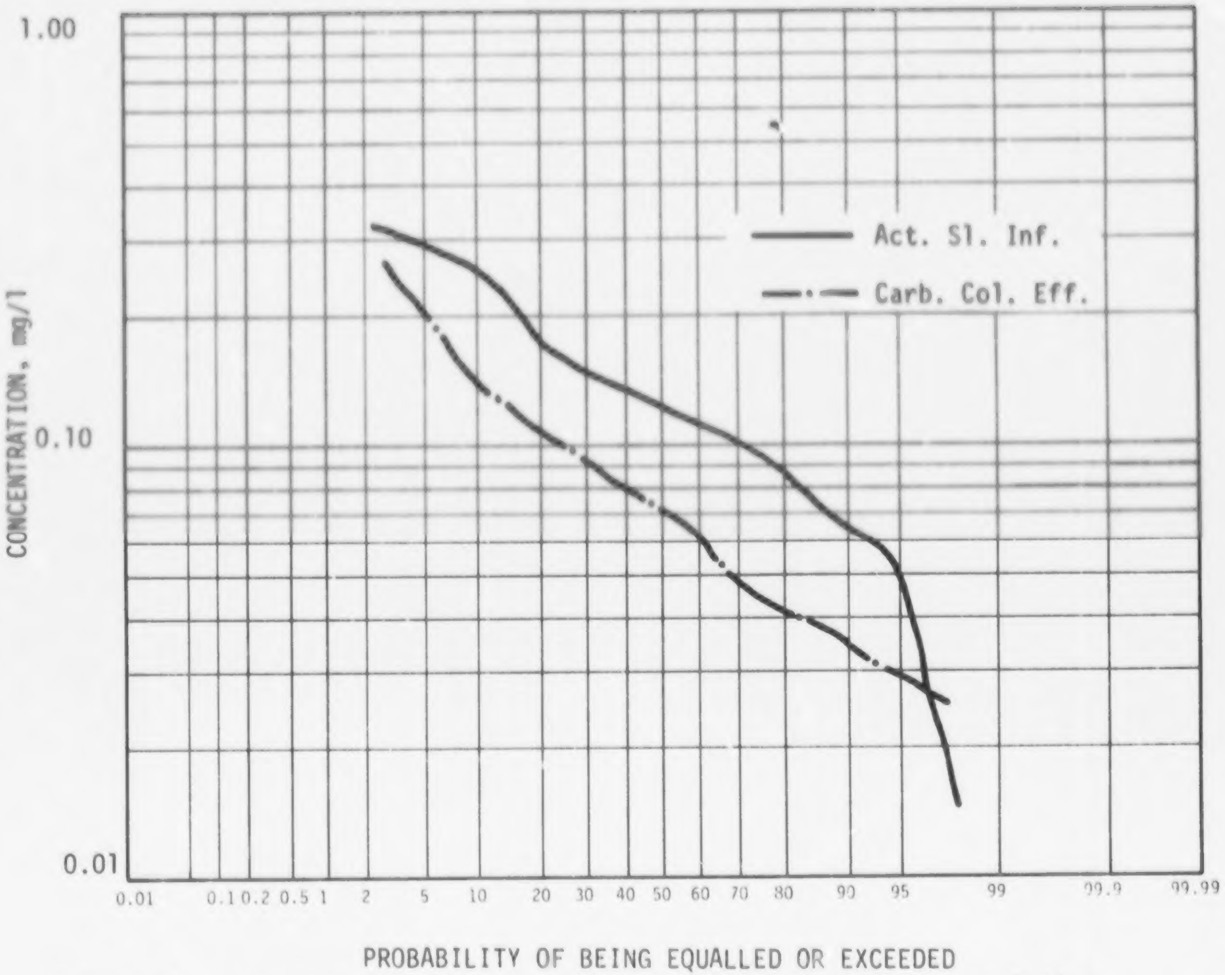

Figure 58. Frequency distributions for nickel, high-pH lime coagulation and recarbonation study.

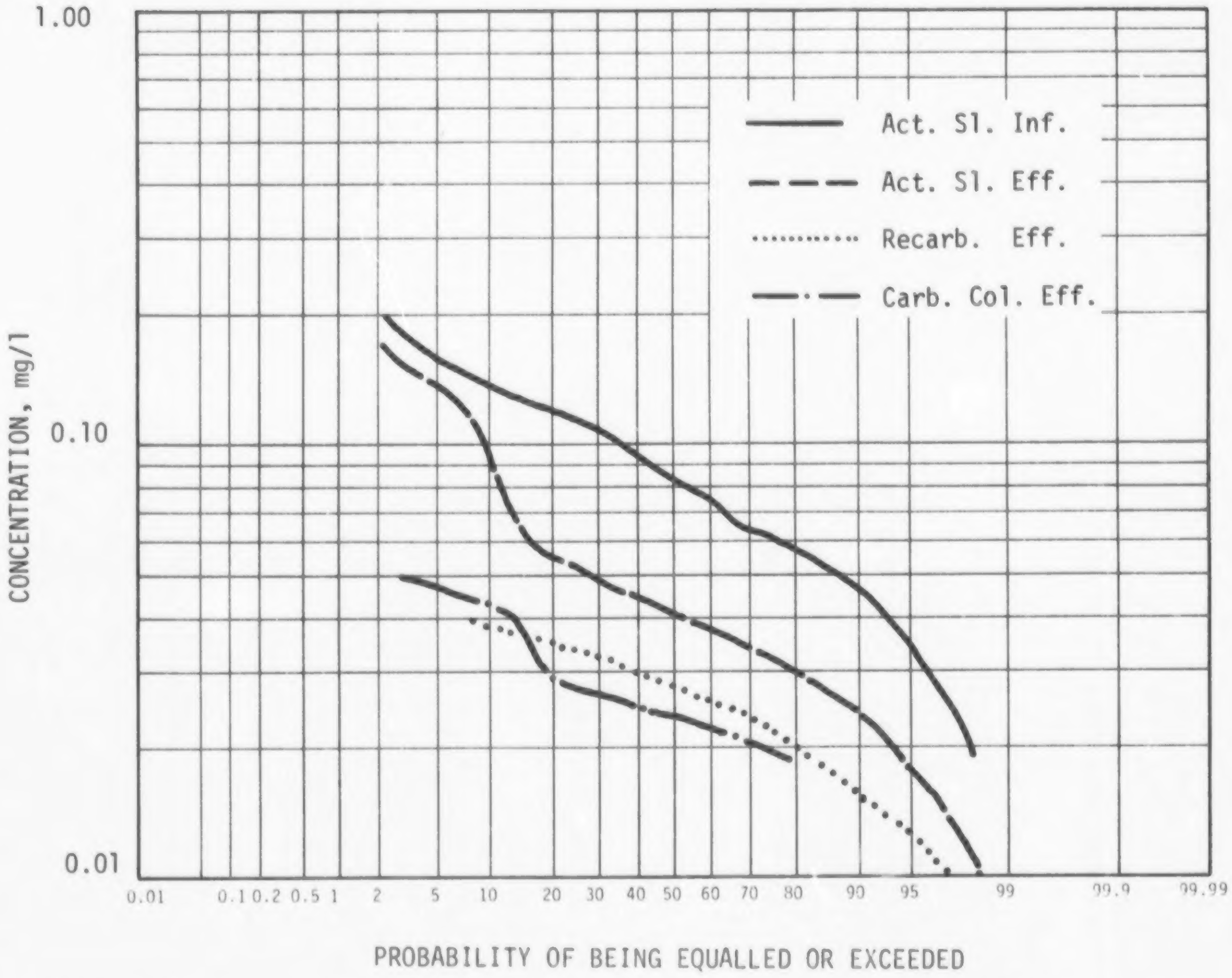

Figure 59. Frequency distributions for lead, high-pH lime coagulation and recarbonation study.

As shown in Figure 60, selenium was removed in the biological, chemical, and physical (carbon) treatment processes. Mean and median removals were 69 percent and 42 percent by activated sludge, 40 percent and 57 percent by high-pH lime clarification, and 58 percent and 100 percent by carbon adsorption. Reductions in the Densator and carbon column exhibited concentration correlations (r=0.45 and 0.98, respectively) but no other correlations. There was no removal of selenium in the multimedia filter. The EPA drinking water standard of 0.01 mg/l was exceeded in 35 percent of the train influent samples, while all train effluent samples were well below the limit.

Silicon

Silicon removal varied between 4 percent and 6 percent through each unit process in the treatment train. The Densator and recarbonation basin together removed 13 percent (mean) or 16 percent (median), the effluent concentration was proportional to TSS (r=0.41) and total P (r=0.55). Also, the reductions in concentration were directly proportional to the methyl orange and phenolphthalein alkalinities (r=0.33 and 0.41, respectively). Multimedia filtration reduced the mean concentration by only 6 percent, and the filter effluent silicon concentration was proportional to effluent TSS (r=0.32) and turbidity (r=0.40). Little or no removal occurred through carbon adsorption.

Strontium

Mean and median removals of strontium were 9 percent and 6 percent in the activated sludge unit, 11 percent and 20 percent in the Densator/recarbonation system. The reductions through chemical treatment exhibited a concentration effect (r=0.42), and the recarbonation basin effluent strontium concentration was proportional to TSS (r=0.38). There was little, if any, significant change in concentration following multimedia and carbon filtration.

The treatment sequence influent and effluent frequency distributions shown in Figure 61 indicate almost no removal, indicating that strontium is a quite refractory material.

Vanadium

Vanadium was removed only by biological treatment and carbon filtration, with mean and median removals of 15 percent and 8 percent in the former, and 43 percent and 37 percent in the latter. There was a mean increase of 0.5 mg/l in the Densator, perhaps originating from contamination in the ferric chloride slurry. The carbon column more than removed this added amount, the reductions exhibiting a concentration effect (r=0.54). Mean and median train removals of vanadium were 39 percent and 28 percent, respectively.

Zinc

Zinc was efficiently removed by the activated sludge unit and the

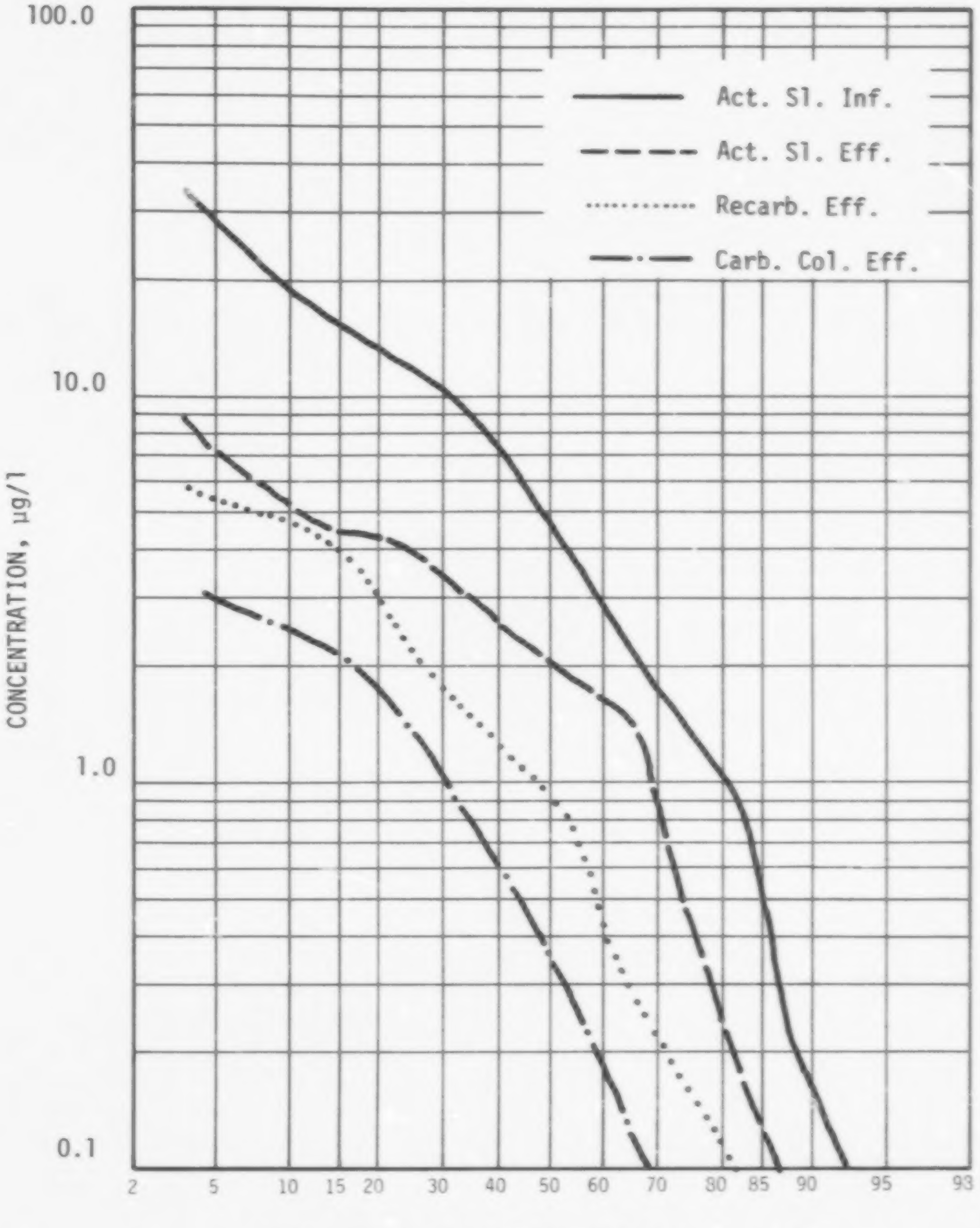

Figure 60. Frequency distributions for selenium, high-pH lime coagulation and recarbonation study.

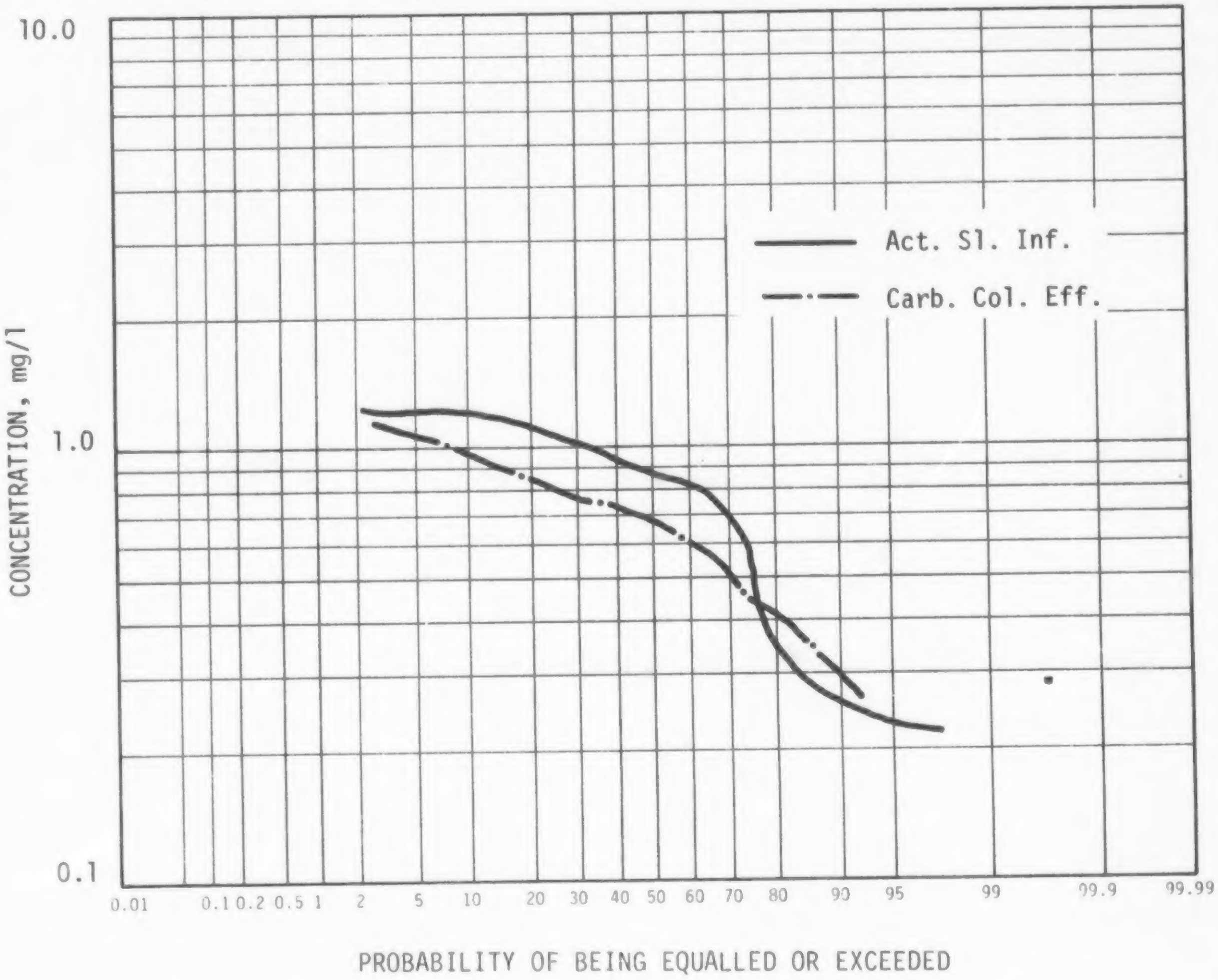

Figure 61. Frequency distributions for strontium, high-pH lime coagulation and recarbonation study.

Densator. Mean and median removals averaged 34 percent to 50 percent, and 36 percent to 56 percent, respectively. However, the galvanized finish on the recarbonation basin was vigorously attacked, resulting in a large increase in zinc during recarbonation. The average mean and median increases came to 0.57 mg/l (675 percent) and 0.39 mg/l (975 percent), respectively, which more than negated the prior removals. Subsequently, there were only minor removals through filtration and carbon adsorption, such that the mean concentration of zinc increased by 0.41 mg/l (205 percent) through the treatment train. Fortunately, not a single sample violated the Secondary Regulations recommendation of 5.0 mg/l, in spite of zinc's erratic behavior in the treatment train. It should be noted that soon after termination of the grant, the amount of zinc emanating from the recarbonation basin started to decline, finally reaching the point where no additions were occurring. At this point all of the galvanizing had been removed by corrosion and the bare steel tank rusted quickly.

SECTION 9

RESPONSES OF INDIVIDUAL METALS

BIOLOGICAL TREATMENT

The period of investigation for metals ran from June 1, 1972 through January 31, 1974, a total of 610 days. The treatment processes of most concern were the Densator, filter, and carbon column, operated in series. Each of three basic types of chemical treatment were studied: Lime only, alum, and lime with recarbonation. It was determined by the pilot plant research staff that the only requirement as to the type of wastewater to be treated was that the feed to the Densator be a well-nitrified wastewater.

The requirement for nitrification resulted from the planning of the virus removal studies (discussed in a subsequent section of this report), in which low ammonia nitrogen concentrations were considered essential to proper disinfection with chlorine.

Since adequate nitrification did not occur in the White Rock Plant, it became necessary to operate the Demonstration Plant's No. 1 activated sludge unit in a nitryfying mode as pre-treatment to the physical/chemical processing. Although the activated sludge unit is considered a basic part of the treatment train, its function with respect to grant requirements was strictly pre-treatment.

Due to the limited size and capacity of the aeration equipment it was not possible to maintain nitrification for protracted periods on primary effluent feed. The wastewater sources at the White Rock Plant which were utilized during the investigation included primary effluent, stage 1 trickling filter effluent, stage II trickling filter effluent, and final effluent. Table 50 identifies the periods of operation on each source (s). From August 2-8, 1972, the No. 1 aeration basin was drained for modifications to the aeration equipment and installation of an additional air compressor, during this time the No. 2 aeration basin was substituted for the No. 1 unit. (Unless specifically referred to as No. 1 or No. 2, the activated sludge data in this report include this week-long period in August.)

Two other periods of particular interest are August 16-17 and August 30 through November 26, 1972, in which the activated sludge influent was a combination of primary effluent and unsettled stage II effluent. Although the exact volumetric ratio of each will never be known, estimates at the time indicated about a 50/50 mixture. In the light of the grant requirements, and since the activated sludge influent stream was always sampled,

TABLE 50. ACTIVATED SLUDGE INFLUENT, JUNE 1972 THROUGH JANUARY 1974

DATES		
FROM	THRU	SOURCE
6-1-72	8-1-72	Unsettled stage II trickling filter effluent.
8-2-72	8-8-72	Unsettled stage II trickling filter effluent, No. 2 aeration basin in service in place of No. 1 aeration basin.
8-9-72	8-15-72	Unsettled stage II trickling filter effluent, No. 1 aeration basin back in service.
8-16-72	8-17-72	Combination of unsettled stage II and primary effluents.
8-18-72	8-29-72	Primary effluent.
8-30-72	11-26-72	Combination of unsettled stage II and primary effluents.
11-27-72	6-8-73	Unsettled stage II trickling filter effluent.
6-9-73	6-20-73	White Rock final effluent.
6-21-73	--	Unsettled stage II trickling filter effluent.
6-22-73	--	White Rock final effluent.
6-23-73	8-31-73	Unsettled stage II trickling filter effluent.
9-1-73	10-10-73	White Rock final effluent.
10-11-73	10-20-73	Unsettled stage II trickling filter effluent.
10-21-73	11-19-73	Unsettled stage I trickling filter effluent.
11-20-73	1-31-74	White Rock final effluent.

the exact proportion of primary and stage II effluent in the influent is not germane to the project. One may correctly assume that the metals content of primary effluent is generally higher than final effluent; and in this regard, every effort was made to operate on the strongest wastewater source and yet provide nitrification.

Table 51 presents the average operating and process control parameters for the No. 1 activated sludge system during the entire 610-day period of investigation. The associated wastewater characteristics follow them on Table 52. There was a considerable variation in the operation of the system, depending upon the time of year, organic loading, etc. The activated sludge effluent quality was relatively constant, because the process control parameters were adjusted in order to maintain consistency in quality. During most of the period, effluent NH_3 -N remained less than 1.0 mg/l. Occasional temporary loss of complete nitrification, lasting perhaps a week to ten days at a time, caused the average concentration to slightly exceed 2 mg/l. Control of effluent BOD_5 and TSS was not easy because of uncontrolled denitrification that occurred in the clarifier. However, filtration of the activated sludge effluent indicated that about 80 percent of the BOD_5, and roughly half of the COD were associated with the particulate fraction. All the parameters shown on Table 52 were analyzed on a daily basis except for TDS and BOD_5, which were generally analyzed every fourth day.

Summaries of the metals analyses on activated sludge influent and effluent covering the entire period of investigation can be found on Tables 53 and 54, respectively. The tables list the median, mean, and standard deviations, maximum and minimum concentrations, and number of samples. Infrequent extreme concentrations on some of the metals tended to weight the mean high. Hence, the median values have particular significance, since in many instances they are more truly representative of ambient conditions. In most cases, the mean values do in fact exceed the medians, the relative difference representing the influence of extreme values.

Because the activated sludge process operated independently of the downstream processes, the activated sludge metals data covering the entire period of investigation are presented separately in this subsection. In a practical sense, the following comments will be applicable to the performance of the biological process within each of the three treatment sequences studied.

Silver

It became evident early into the investigation that very little silver was present in Dallas' raw wastewater, in spite of some photographic industries connected to the sanitary sewer. Measureable amounts were found in only 28 percent of the activated sludge influent samples and 21 percent of the effluent samples. The maximum concentration ever observed was five times lower than the current drinking water MCL of 0.05 mg/l. Although a slight removal is indicated from the mean concentrations, silver was not present at high enough levels to develop any definitive information

TABLE 51. HYDRAULIC AND PROCESS CONTROL FOR THE ACTIVATED SLUDGE PROCESS

HYDRAULIC OPERATION	
Q (influent)	10.79 l/sec (171 gpm)
Q (return)	10.3 l/sec (163 gpm)
Q (waste)	6964 l/day (1840 gpd)
Aeration T	1.95 hours
Clarifier overflow rate(Q_i)	14.2 m^3/day-m^2 (348 gal/ft^2-day)
Weir loading	33.6 m^3/day-m 2706 gal/ft/day
Clarifier T (Q_i+Q_r)	2.76 hours
PROCESS CONTROLS	
MLSS	3608 mg/l
MLVSS	2619 mg/l
RAS	7241 mg/l
SVI	186 mg/l
Air supplied	19.1 l/sec. (405 cfm)
D. O.	2.8 mg/l
D. O. Uptake rate	36.7 mg/l-hr.
F/M (COD)	0.366 day^{-1}
F/M (SOC)	0.039 day^{-1}
F/M (BOD)	0.106 day^{-1}
Sludge Age	7.9 days
Temperature	24°C (76°F)

TABLE 52. PERFORMANCE SUMMARY, NO. 1 ACTIVATED SLUDGE SYSTEM

PARAMETER	A.S. INFLUENT (mg/1)	A.S. EFFLUENT (mg/1)	REMOVAL percent
COD	241	60	75.1
TOC, soluble	26	11	57.7
BOD	70	30	57.1
TSS	137	29	78.8
TDS	522	511	2.1
SC, μmho/cm	788	717	9.0
NH_3-N	14.0	2.3	83.6
Org. N	9.8	4.0	59.2
NO_2+NO_3-N	1.1	8.9	--
NO_2-N,	0.12	0.2	--
Total P	10.1	8.0	20.8
pH, units	7.3	7.1	--
T. Alk. as $CaCO_3$	208	116	44.2
P. Alk. as $CaCO_3$	0	0	--
Total Count, per ml	2.1×10^6	4.9×10^4	97.7
Total MPN, per 100 ml	2.0×10^7	5.5×10^5	97.3
Fecal MPN, per 100 ml	2.5×10^6	3.8×10^4	98.5

TABLE 53. ACTIVATED SLUDGE INFLUENT METALS SUMMARY JUNE 1972 - JANUARY 1974

	MEDIAN	MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.78	1.73	10.0	0.0	58
Al	0.63	0.66	0.30	1.80	0.18	91
As*	9.5	14.8	16.6	119.0	0.0	153
B	0.36	0.37	0.082	0.65	0.16	149
Ba	0.120	0.129	0.068	0.48	0.01	168
Be*	0.010	0.014	0.013	0.04	0.0	23
Ca	52.0	54.6	16.8	144.0	31.0	181
Cd*	11.0	14.0	12.5	119.0	0.0	222
Co	0.035	0.039	0.020	0.12	0.0	183
Cr	0.180	0.205	0.127	0.75	0.015	222
Cu	0.140	0.224	0.225	1.04	0.0	181
Fe	0.99	1.07	0.63	7.80	0.28	181
Hg*	0.34	0.43	0.47	3.2	0.0	111
K	14.6	14.5	1.2	16.8	11.8	58
Mg	5.18	5.18	0.86	8.12	1.62	129
Mn	0.075	0.076	0.018	0.13	0.04	182
Mo*	5.0	15.2	29.5	170.0	0.0	38
Na	102.0	99.5	19.8	148.0	33.0	145
Ni	0.099	0.109	0.062	0.38	0.01	159
Pb	0.100	0.108	0.052	0.45	0.0	218
Se	4.2	7.2	8.0	40.0	0.0	115
Si	9.4	9.8	2.4	17.0	3.9	53
Sr	0.88	0.79	0.32	1.25	0.23	41
V*	3.6	3.9	1.4	8.5	0.5	49
Zn	0.270	0.366	0.424	4.10	0.05	182

Concentration in mg/l (*μg/l)

TABLE 54. ACTIVATED SLUDGE EFFLUENT METALS SUMMARY JUNE 1972 - JANUARY 1974

	MEDIAN	MEAN	σ	MAX.	MIN.	N
Ag*	0.0	0.38	0.85	3.0	0.0	58
Al	0.29	0.44	0.53	3.50	0.02	92
As*	9.0	13.4	12.9	85.0	0.0	156
B	0.36	0.37	0.075	0.60	0.17	151
Ba	0.060	0.070	0.047	0.36	0.0	169
Be*	0.0	0.005	0.008	0.03	0.0	23
Ca	47.4	51.9	17.1	118.0	26.5	182
Cd*	6.0	7.1	4.6	30.0	0.0	223
Co	0.030	0.036	0.023	0.13	0.0	184
Cr	0.060	0.071	0.053	0.56	0.002	223
Cu	0.051	0.072	0.076	0.69	0.01	182
Fe	0.35	0.61	1.41	14.90	0.07	182
Hg*	0.15	0.26	0.33	2.2	0.0	111
K	14.1	14.1	1.2	16.5	11.2	58
Mg	5.01	4.96	0.64	6.60	2.43	130
Mn	0.052	0.056	0.028	0.25	0.003	183
Mo*	2.4	3.6	3.9	15.4	0.0	39
Na	96.5	97.2	19.8	150.0	45.0	146
Ni	0.075	0.082	0.040	0.28	0.0	160
Pb	0.040	0.050	0.036	0.30	0.0	220
Se*	1.0	1.7	2.1	9.0	0.0	119
Si	9.4	9.4	2.2	13.5	4.6	54
Sr	0.83	0.72	0.30	1.19	0.16	42
V*	3.0	3.3	1.3	8.0	1.3	52
Zn	0.110	0.139	0.115	1.06	0.04	183

Concentration in mg/l (*μg/l)

concerning its removal.

Aluminum

Aluminum removals by activated sludge averaged 33 percent (mean) or 55 percent (median). However, the effluent concentrations were much more variable than the influent, and exceeded the influent concentrations approximately 10 percent of the time. The influent frequency distribution was log-normal, whereas the effluent distribution clearly followed a bimodal pattern. Both the percentage of aluminum removed and the amount removed exhibited a pronounced concentration effect, *i.e.*, directly proportional to the influent concentration. Aluminum removal also correlated somewhat with COD removal, the highest removals occurring at COD removals of 70 percent or more. High effluent concentrations also coincided with high effluent COD and TSS.

Arsenic

Arsenic was not significantly removed by biological treatment, although a slight overall decrease of 9 percent was obtained. The activated sludge unit did appear to smooth the fluctuations in influent concentrations. The drinking water MCL of 0.05 mg arsenic per liter was exceeded only 3 percent of the time in both the influent and effluent. The removals exhibited a weak concentration effect, but zero or negative removals occurred on a 47-percent frequency.

Boron

Boron was refractory to biological treatment, with no significant removals or increases through the activated sludge process. Based on mean values, a 9 percent reduction was observed; however, there was no removal on the basis of median values. The highest influent concentration observed during the entire period of investigation was only 0.65 mg/l.

Barium

Removals of barium in the activated sludge unit average 46 percent by means, 50 percent by medians. Reductions in concentration exhibited a concentration effect at all influent concentrations (r=0.75), but a plot of effluent versus influent concentrations was also linear (r=0.67). COD removal and effluent COD and TSS concentrations behaved in a manner similar to effluent barium concentrations.

Beryllium

Analyses for beryllium were performed on a total of 23 days scattered over a period of 5 months. The concentrations observed in the activated sludge influent were exceedingly low, the highest being only 0.04 mg/l. An average reduction of about 64 percent occurred through biological treatment, but most of the effluent concentrations (61 percent) were below the detection limit. Beryllium reductions did exhibit a strong concentration effect at all influent concentrations (r=0.89), but the limited amount of data prohibited any conclusive observations.

Calcium

The activated sludge influent calcium concentration averaged 54.6 mg/l, and varied from 31 mg/l to 114 mg/l. The overall removal was 5 percent (mean), or 9 percent (median). No significant correlations or removal patterns were ever observed.

Cadmium

A significant removal of cadmium occurred during activated sludge treatment, 49 percent by means, 45 percent by medians. A very pronounced concentration correlation was observed for all influent concentrations (r=0.94). The only occasions when zero or negative removals occurred was when the influent concentration was less than about 10 mg/l. The relative fluctuations in concentration were also lower on the effluent than on the influent. In general, effluent concentrations increased with COD and TSS. The highest concentrations of cadmium in the effluent happened to coincide with low dissolved oxygen in the aeration basin (<1.0 mg/l), but cadmium removals were not particularly influenced by the residual dissolved oxygen concentration in the mixed liquor.

Cobalt

Some cobalt roughly 8 percent (by means) to 14 percent (by medians), was removed through activated sludge. No removal patterns or correlations were observed.

Chromium

Chromium was significantly removed by the activated sludge process. The average removals were 66 percent (mean) to 67 percent (median), and the removals were very consistent. Chromium reductions exhibited a classical concentration correlation at all influent concentrations. A graph showing the reductions versus influent concentrations appears on Figure 62. The linear correlation coefficient for the estimating equation is: r=0.92 (N=222). The percentage of chromium removed also exhibited a concentration correlation. In addition, COD removal was proportional to percent chromium removal (r=0.62) and chromium reductions (r=0.45).

Copper

Copper removals averaged 68 percent by means or 64 percent by medians. The distribution of concentrations was skewed toward high values in the influent and low values in the effluent, atypical of the patterns observed for the other metals. Like chromium, the reductions in concentration through the activated sludge unit were strongly concentration-dependent at all influent concentrations (r=0.94). The removals also correlated directly with COD removal and inversely with TSS. Significant copper removals were observed, mainly during nitrifying operations.

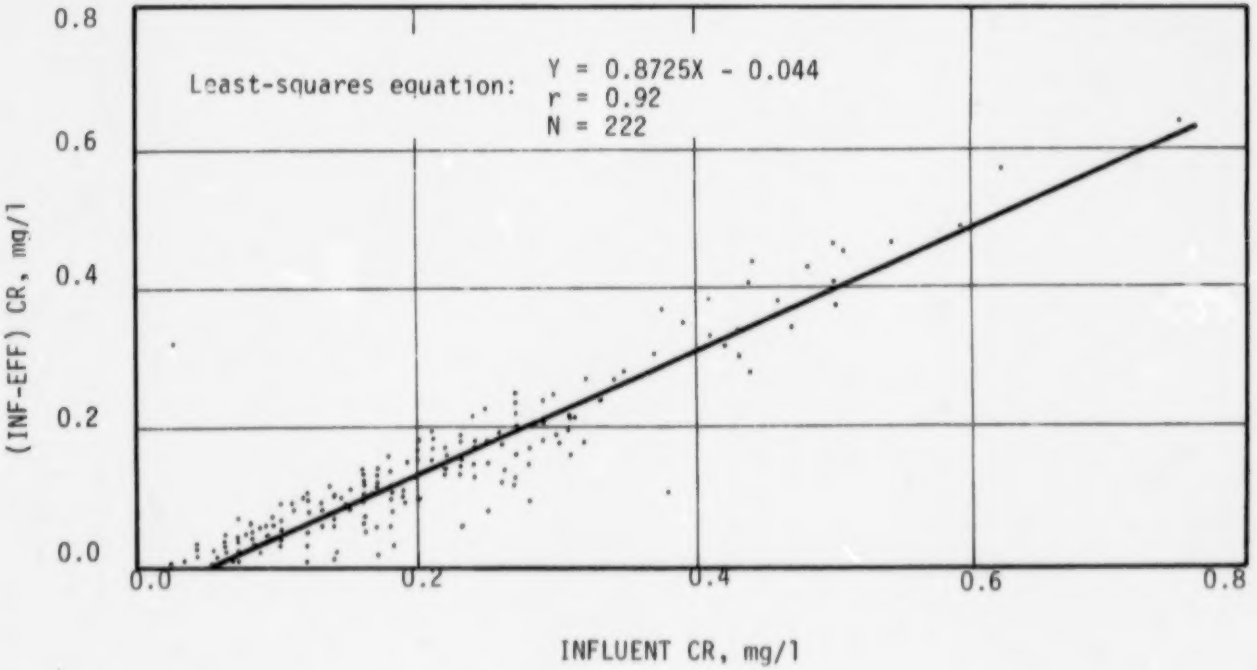

Figure 62. Chromium reductions vs influent concentrations, showing a typical concentration effect: No. 1 activated sludge unit.

Iron

As expected, iron was significantly removed by the activated sludge process, 43 percent (mean), 64 percent (median). Probability distributions reflect a log-normal pattern for the influent and a bimodal relationship for the effluent, skewed toward the high side. Only one extreme value was picked up on the influent, compared to at least eight on the effluent. However, effluent iron concentrations exceeded influent iron only at influent concentrations less than 1.0 mg/l. Iron reductions exhibited a strong concentration effect (r=0.80), and the correlation between iron and TSS was reasonably good (r=0.66). All effluent concentrations of iron greater than 1.0 mg/l accompanied TSS concentrations greater than 45 mg/l. The EPA Secondary Regulations recommendation of 0.3 mg/l was exceeded in 99 percent of the influent samples and in 59 percent of the effluent samples.

Mercury

Mercury removals could be characterized as moderate, ranging from 22 percent (means) to 42 percent (medians). The activated sludge influent concentrations exceeded the EPA maximum contaminant level for drinking water (0.002 mg/l) on only 2 percent of the samples and the activated sludge effluent exceeded this concentration in about 1 percent of the samples.

No extreme values, or radical variations in the distribution, were observed. Negative removals occurred on 30 out of 110 sample days, zero removals occurred on 5 days. Reductions in mercury were strongly concentration-dependent at all influent concentrations, and inversely related to effluent NH_3-N. The largest reductions in mercury coincided with low effluent NH_3-N.

Potassium

Potassium was essentially unaffected by biological treatment, but a net overall removal of 3 percent (mean and median) was obtained. Sludge age and MLSS were the only parameters which demonstrated any correlation with potassium removal. In general, the removals increased with both sludge age and MLSS. No concentration effects were observed.

Magnesium

Magnesium was poorly removed by the activated sludge process, 4 percent (mean) and 3 percent (median). A concentration effect was evident at influent concentrations greater than about 5.0 mg/l (r=0.67), the reductions increasing at higher concentrations. The largest removal, 34 percent, occurred at the highest influent concentration, 8.1 mg/l. Sludge age also appeared to exert a minor effect on magnesium removal.

Manganese

Manganese removals averaged 26 percent (mean) or 30 percent (median), varying from a minus 156 percent to a positive 96 percent. However, there were no extreme values in either the influent or effluent samples. Mn reductions exhibited a concentration correlation (r=0.42), but negative removals occurred in 8 percent of the paired samples. Correlations between effluent NH_3-N, COD, and TSS concentrations, and manganese reductions revealed inverse relationships in each case (r=0.46, -0.49, -0.45, respectively). The EPA Secondary Regulations recommendation of 0.05 mg/l was exceeded in 91 percent of the influent samples and 51 percent of the effluent samples.

Molybdenum

Substantial removal of molybdenum occurred through biological treatment, 77 percent by means and 52 percent by medians. Complete (100 percent) removal occurred on 7 out of 38 paired samples. The activated sludge system provided considerable buffering for extreme influent values, the influent and effluent probability distributions being quite dissimilar. The influent probability distribution was skewed toward high values. Molybdenum reductions also exhibited a pronounced concentration effect at all influent concentrations (r=0.99).

Sodium

Sodium, like potassium, was poorly removed during biological treatment. However, a mean removal of 2 percent and a median removal of 5 percent was obtained on the 145 paired samples. The greatest reductions were obtained at low F/M ratios, although the relative effect was minor. There were no extreme values of sodium, and the highest concentration was 150 mg/l, roughly 50 percent over the mean value.

Nickel

An average 25 percent removal of nickel occurred through biological treatment, based on both means and medians. Reductions exhibited a strong concentration effect at all influent concentrations greater than about 0.06 mg/l (r=0.78), with negative removals occurring frequently at lesser values. Nickel reductions varied inversely with effluent NH_3-N, COD, and TSS concentrations. There were no extreme values of nickel in either the influent or the effluent samples.

Lead

Lead was significantly removed by the activated sludge system, 53 percent (mean) and 60 percent (median). The reductions exhibited a strong concentration effect at all influent concentrations (r=0.78). A reasonably good correlation was observed between lead removal and COD removal (r=0.52). Likewise, high effluent TSS and COD often accompanied low lead removals. Out of 218 influent samples there were only two extreme values (0.35 mg/l and 0.45 mg/l), which were readily damped by the unit. The drinking water MCL of 0.05 mg/l was exceeded in 88 percent of the influent samples and 31 percent of the effluent samples.

Selenium

Selenium removal averaged 76 percent by both means and medians, ranging from negative removal to 100 percent removal. Reductions in selenium were strongly concentration-dependent over the entire range of influent concentrations (r=0.97). The activated sludge system provided consistent buffering against high concentrations in the effluent. Removals were higher at sludge ages greater than about 15 days. Also, correlations in selenium reduction versus effluent COD and NH_3-N were both inversely related. The drinking water limit of 0.01 mg/l was exceeded in 24 percent of the influent samples, but none of the effluent samples.

Silicon

Biological removal of soluble silicon averaged only 5 percent by means, zero by medians. No similarities in removal patterns were observed between silicon and other chemical species.

Strontium

Strontium removal averaged 9 percent (mean) and 6 percent (median), and appeared to increase with increasing MLSS and decrease with increasing F/M, COD, and TSS. The frequency distribution of both the influent and effluent adhered to a bimodal pattern, almost devoid of values in the 0.30-0.65 mg/l range. However, there were no extreme values in either case.

Vanadium

Removal of vanadium averaged 14 percent (mean) and 17 percent (median) varying considerably within the range from a negative 160 percent to a positive 100 percent. A slight concentration effect appeared to bias the reduction when the influent exceeded about 3.0 mg/l (r=0.49). It appears that higher removals accompanied higher MLSS concentrations in the aeration basin, but the lack of sufficient data limited any further analyses. No extreme values were found in either the influent or the effluent samples.

Zinc

An averaged removal of 62 percent (mean) or 59 percent (median) was observed for zinc over the period of investigation. Reductions through the activated sludge process clearly exhibited a concentration effect (r=0.96). There appeared to be a positive correlation between zinc reduction and COD removal, and negative correlations between zinc reduction and effluent NH_3-N, COD, and TSS. A few extreme values appeared on the influent samples, but none in the effluent. At no time did the concentration of zinc in any sample reach the EPA recommended drinking water MCL of 5.0 mg/l.

THE THREE COMBINATIONS OF TREATMENT SEQUENCES

During the 610-day period covered by this report the Demonstration Plant of the Dallas Water Reclamation Research Center was configured in the three separate advanced wastewater treatment (AWT) sequences that have been described in detail. Tables 55 through 57 are the summaries of the analytical data for each phase of the project, with the exception of the metals data which are summarized in Tables 58 through 60.

Although the study of disinfection per se was not a direct part of this research effort (with the very obvious exception of the virus studies reported in the following section), it is interesting to evaluate the microbiological data presented in Tables 55, 56, and 57. During the high-pH lime coagulation study (Phase I) the upflow clarifier was very effective as a disinfection process, and since the effluent pH was not neutralized, regrowth or recontamination was not observed.

The alum coagulation study constituted Phase II of the project, and the reductions in coliform organisms resulting from the chemical treatment process were only slightly greater than one log.

Phase III, high-pH lime coagulation and recarbonation, resulted in significant reductions in bacterial populations; however, the neutralized effluent was susceptible to recontamination and regrowth.

The influent and effluent mean metals concentrations and the corresponding removals are shown for all three phases in Table 61, while Table 62 presents similar information based on median concentrations.

Silver

Silver was not usually present in a concentration high enough to permit evaluation of its response to the various unit processes.

Aluminum

Aluminum had the highest removal (78 percent based on medians) during the alum coagulation phase; however, the removal decreased to five percent when evaluated in terms of mean concentrations. The lime coagulation and recarbonation phase yielded a consistent removal of 77 percent (mean) and 75 percent (median); furthermore, this was the only instance when the AWT processes reduced the arithmetic mean aluminum concentration in the effluent.

Arsenic

Arsenic was effectively removed by the AWT processes, and only slightly affected by the activated sludge process, as shown in Figure 63. The lime and recarbonation study constituted the most successful treatment sequence which resulted in removals of 83 percent (mean) and 79 percent (median).

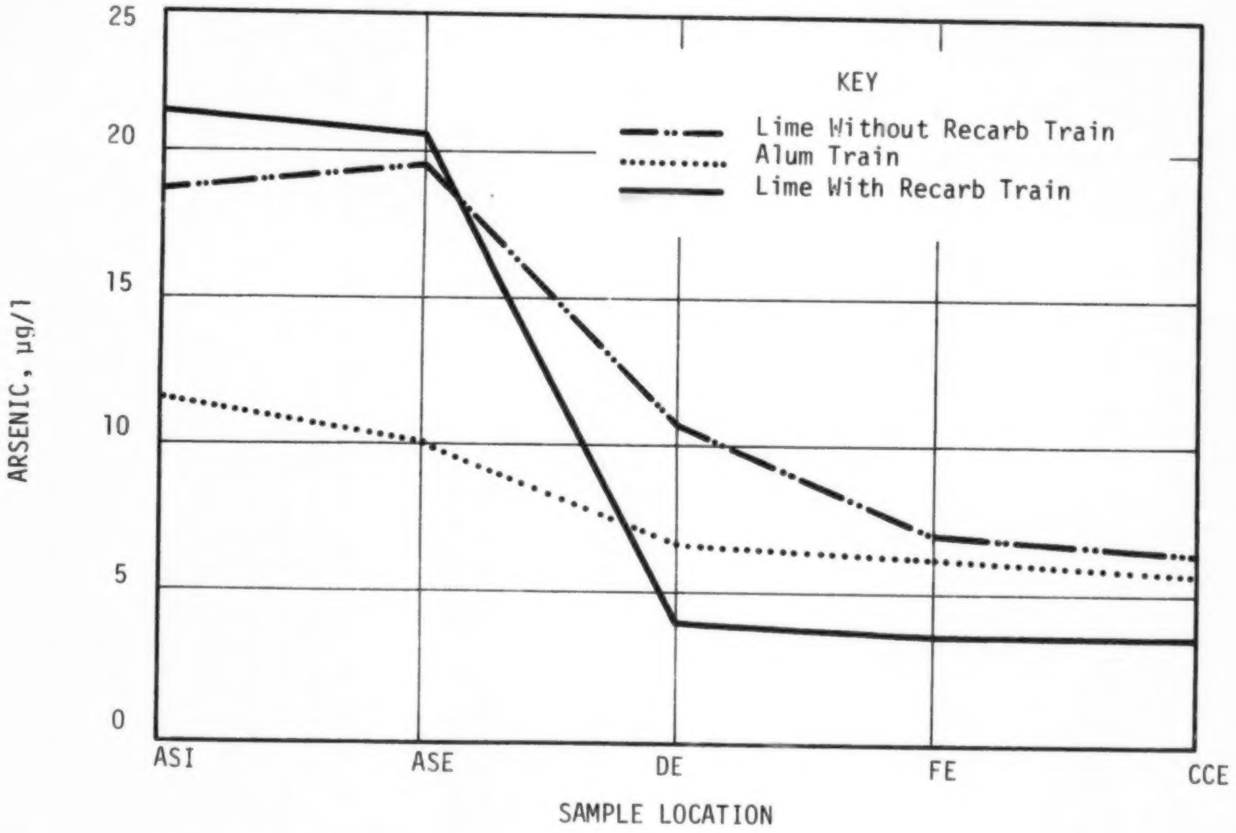

Figure 63. Arsenic levels in wastewater after treatment by secondary and tertiary processes.

TABLE 55. ANALYTICAL DATA SUMMARY HIGH -pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

PARAMETER	ACTIVATED SLUDGE INFLUENT	ACTIVATED SLUDGE EFFLUENT	DENSATOR EFFLUENT	MULTIMEDIA FILTER EFFLUENT	CARBON COLUMN EFFLUENT
COD	273	91	27	28	16
TOC, soluble	42	19	9	--	6
BOD_5	88	28	4	4	3
TSS	124	27	46	12	7
TDS	532	541	680	642	642
SC, μmho/cm	819	739	1355	1384	1349
NH_3-N	16.1	4.4	2.6	2.2	3.7
Org. N	9.5	4.9	2.3	2.2	1.8
NO_2+NO_3-N	0.77	8.2	9.7	9.7	9.4
NO_2-N	0.06	0.59	0.95	1.09	1.28
Total P	11.0	9.5	0.99	0.41	0.16
pH, units	7.3	7.1	11.5	11.5	11.5
T. Alk. as $CaCO_3$	210	114	265	274	253
P. Alk. as $CaCO_3$	0	0	228	237	228
Total Count, per ml	5.2×10^6	2.0×10^5	13	8	6
Total MPN, per 100 ml	6.2×10^7	1.4×10^6	3	<2	<2
Fecal MPN, per 100 ml	6.3×10^6	8.0×10^4	2	<2	<2

Concentrations in mg/l except as noted. --: Not Available

TABLE 55. ANALYTICAL DATA SUMMARY ALUM TREATMENT
NOVEMBER 1972 - OCTOBER 1973

PARAMETER	ACTIVATED SLUDGE INFLUENT	ACTIVATED SLUDGE EFFLUENT	DENSATOR EFFLUENT	MULTIMEDIA FILTER EFFLUENT	CARBON COLUMN EFFLUENT
COD	237	57	28	26	13
TOC, soluble	20	10	8	8	4
BOD_5	62	28	6	3	<2
TSS	142	28	17	7	2
TDS	507	498	532	515	491
SC, µmho/cm	750	691	723	710	711
NH_3-N	13.82	2.36	2.04	2.08	1.71
Org. N	10.06	3.85	2.39	2.10	1.49
NO_2+NO_3-N	1.2	8.4	8.6	8.6	8.5
NO_2-N	0.126	0.076	0.104	0.148	0.217
Total P	9.8	7.8	3.0	2.4	1.9
pH, units	7.3	7.2	7.6	7.5	7.5
T. Alk. as $CaCO_3$	206	126	120	117	114
P. Alk. as $CaCO_3$	0	0	5	4	3
Total Count, per ml	1.3×10^6	5.1×10^4	4.0×10^3	2.6×10^3	6.9×10^2
Total MPN, per 100 ml	1.3×10^7	4.2×10^5	2.3×10^4	1.3×10^4	6.5×10^3
Fecal MPN, per 100 ml	1.8×10^6	3.1×10^4	1.8×10^3	1.5×10^3	6.3×10^2

Concentrations in mg/l except as noted.

TABLE 57. ANALYTICAL DATA SUMMARY HIGH-pH LIME TREATMENT WITH RECARBONATION NOVEMBER 1973 - JANUARY 1974

PARAMETER	ACTIVATED SLUDGE INFLUENT	ACTIVATED SLUDGE EFFLUENT	DENSATOR EFFLUENT	RECARB. EFFLUENT	MULTIMEDIA FILTER EFFLUENT	CARBON COLUMN EFFLUENT
COD	217	65	28	27	25	8
TOC, soluble	27	11	9	9	7	3
BOD_5	69	38	4	5	4	2
TSS	133	44	75	33	5	4
TDS	557	536	633	598	645	637
SC, µmho/cm	851	762	1084	919	974	981
NH_3-N	14.47	1.90	2.70	2.36	2.78	2.73
Org. N	9.09	4.43	1.92	2.21	2.15	1.11
NO_2+NO_3-N	0.9	9.9	10.7	9.5	10.4	10.8
NO_2-N	0.11	0.053	0.096	0.118	0.131	0.117
Total P	10.2	7.4	1.3	1.0	1.0	0.9
pH, units	7.2	7.1	10.5	7.0	6.6	6.8
T. Alk. as $CaCO_3$	215	129	204	221	230	236
P. Alk. as $CaCO_3$	0	0	130	12	0	0
Total Count, per ml	1.9×10^6	9.3×10^3	18	2.3×10^3	1.9×10^4	3.3×10^3
Total MPN, per 100 ml	1.4×10^7	3.2×10^5	8	2.3×10^2	9.4×10^2	1.3×10^2
Fecal MPN, per 100 ml	4.2×10^6	2.5×10^4	6	1.7×10^2	2.9×10^2	59

Concentrations in mg/l except as noted.

TABLE 58. SUMMARY OF MEAN CONCENTRATIONS, HIGH-pH LIME TREATMENT WITHOUT RECARBONATION JUNE, AUGUST-OCTOBER 1972, NOVEMBER-DECEMBER 1973

METAL	A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	FILTER EFFLUENT	CARBON EFFLUENT
Ag*	0.62	0.26	0.94	0.94	0.62
Al	0.92	0.38	0.20	0.29	0.36
As*	18.7	19.5	10.8	7.0	6.4
B	0.39	0.42	0.41	0.41	0.39
Ba	0.149	0.079	0.083	0.092	0.091
Ca	45.0	42.5	156.1	156.1	144.9
Cd*	13.3	7.6	7.6	7.4	7.2
Co	0.045	0.037	0.058	0.057	0.054
Cr	0.209	0.085	0.012	0.009	0.0095
Cu	0.138	0.080	0.056	0.066	0.071
Fe	1.05	0.34	0.30	0.12	0.064
Hg*	0.53	0.29	0.14	0.094	0.11
K	14.7	14.3	14.5	14.7	14.5
Mg	5.27	4.97	0.99	0.66	0.58
Mn	0.071	0.051	0.010	0.0061	0.0067
Mo*	2.5	2.1	4.2	1.7	1.9
Na	108.8	108.1	117.3	117.1	117.5
Ni	0.104	0.082	0.052	0.042	0.029
Pb	0.100	0.044	0.039	0.040	0.043
Se*	14.2	2.4	1.9	2.04	1.00
Si	10.0	9.6	13.4	6.7	8.8
Sr	0.27	0.24	0.23	0.23	0.23
V*	4.6	4.2	3.6	2.4	2.9
Zn	0.323	0.123	0.063	0.048	0.041

Concentrations in mg/l (*μg/l).

TABLE 59. SUMMARY OF MEAN CONCENTRATIONS,
ALUM TREATMENT
NOVEMBER 1972 - OCTOBER 1973

METAL	A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	FILTER EFFLUENT	CARBON EFFLUENT
Ag*	0.0	0.0	0.0	0.0	0.0
Al	0.63	0.42	2.13	0.78	0.60
As*	11.4	10.1	6.8	6.1	5.8
B	0.36	0.35	0.37	0.38	0.35
Ba	0.132	0.065	0.057	0.056	0.056
Be*	0.014	0.005	0.0005	0.012	0.010
Ca	59.3	55.8	69.4	68.6	66.2
Cd*	12.2	5.6	4.1	4.0	3.8
Co	0.029	0.026	0.027	0.027	0.025
Cr	0.236	0.066	0.023	0.019	0.016
Cu	0.33	0.054	0.034	0.056	0.039
Fe	1.28	0.33	0.16	0.13	0.09
Hg*	0.52	0.26	0.32	0.25	0.22
K	13.3	12.7	12.5	12.3	11.6
Mg	4.80	4.67	4.58	4.65	4.55
Mn	0.083	0.055	0.037	0.030	0.023
Mo*	20.9	4.2	3.1	3.8	3.2
Na	92.0	89.2	89.3	88.9	86.4
Ni	0.114	0.079	0.068	0.070	0.058
Pb	0.121	0.054	0.042	0.040	0.040
Se*	4.6	1.1	1.0	1.2	0.6
Si	10.3	9.7	10.4	9.7	9.9
V*	4.8	4.2	3.9	4.0	4.3
Zn	0.520	0.156	0.109	0.106	0.067

Concentration in mg/l(*μg/l)

TABLE 60. SUMMARY OF MEAN CONCENTRATIONS, HIGH-pH LIME TREATMENT WITH RECARBONATION NOVEMBER 1973 - JANUARY 1974

METAL	A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	RECARB. EFFLUENT	FILTER EFFLUENT	CARBON EFFLUENT
Al	0.69	0.47	0.18	0.15	0.21	0.16
As*	21.2	20.6	5.6	3.9	3.5	3.5
B	0.36	0.36	0.38	0.34	0.36	0.32
Ba	0.115	0.075	0.086	0.084	0.094	0.086
Ca	66.2	64.9	105.4	106.1	96.5	101.2
Cd*	13.7	7.3	3.6	3.4	3.3	3.0
Co	0.052	0.048	0.067	0.067	0.062	0.063
Cr	0.114	0.052	0.014	0.011	0.008	0.006
Cu	0.182	0.077	0.050	0.073	0.082	0.054
Fe	0.85	1.45	0.97	0.82	0.24	0.20
Hg*	0.28	0.26	0.11	0.17	0.12	0.08
Mg	5.14	4.96	2.58	2.40	2.61	2.46
Mn	0.079	0.066	0.019	0.016	0.017	0.17
Na	93.8	90.3	90.5	90.0	82.5	81.7
Ni	0.136	0.106	0.087	0.083	0.072	0.078
Pb	0.089	0.050	0.029	0.027	0.026	0.027
Se*	7.8	2.4	1.4	1.5	1.7	0.7
Si	9.7	9.3	8.7	8.1	7.6	7.3
Sr	0.79	0.72	0.66	0.64	0.66	0.64
V*	3.4	2.9	3.4	3.2	3.6	2.0
Zn	0.203	0.133	0.084	0.654	0.532	0.617

Concentrations in mg/l (*µg/l)

TABLE 61. SUMMARY OF MEAN TRAIN REMOVALS

METAL	LIME ONLY			LIME + RECARB			ALUM		
	INF	EFF	%R	INF	EFF	%R	INF	EFF	%R
Ag*	0.62	0.62	0	--	--	--	0.0	0.0	0
Al	0.92	0.36	61	0.69	0.16	77	0.63	0.60	5
As*	18.7	6.4	66	21.2	3.5	83	11.4	5.8	49
B	0.39	0.39	0	0.36	0.32	11	0.36	0.35	3
Ba	0.149	0.091	39	0.115	0.086	25	0.132	0.056	58
Be*	--	--	--	--	--	--	0.014	0.010	29
Ca	45.0	144.9	-222	66.2	101.2	- 35	59.3	66.2	-12
Cd*	13.3	7.2	46	13.7	3.0	78	12.2	3.8	69
Co	0.045	0.054	- 20	0.052	0.063	- 21	0.029	0.025	14
Cr	0.209	0.0095	95	0.114	0.006	95	0.236	0.016	93
Cu	0.138	0.071	49	0.182	0.054	70	0.33	0.039	88
Fe	1.05	0.064	94	0.85	0.20	76	1.28	0.09	93
Hg*	0.53	0.11	79	0.28	0.08	71	0.52	0.22	58
K	14.7	14.5	1	--	--	--	13.3	11.6	13
Mg	5.27	0.58	89	5.14	2.46	52	4.80	4.55	5
Mn	0.071	0.0067	91	0.079	0.017	78	0.083	0.023	72
Mo*	2.5	1.9	24	--	--	--	20.9	3.2	85
Na	108.8	117.5	- 8	93.8	81.7	13	92.0	86.4	6
Ni	0.104	0.029	72	0.136	0.078	43	0.114	0.058	49
Pb	0.100	0.043	57	0.089	0.027	70	0.121	0.040	67
Se*	14.2	1.00	93	7.8	0.7	91	4.6	0.6	87
Si	10.0	8.8	12	9.7	7.3	25	10.3	9.9	4
Sr	0.27	0.23	15	0.79	0.64	19	--	--	--
V*	4.6	2.9	37	3.4	2.0	41	4.8	4.3	10
Zn	0.323	0.041	87	0.203	0.617	-204	0.520	0.067	87

Concentration in mg/l (*μg/l) --: Not Available

TABLE 52. SUMMARY OF MEDIAN TRAIN REMOVALS

	LIME ONLY			LIME + RECARB.			ALUM		
METAL	INF	EFF	%R	INF	EFF	%R	INF	EFF	%R
Ag*	0.0	0.0	--	--	--	--	0.0	0.0	--
Al	0.73	--	--	0.64	0.16	75	0.60	0.13	78
As*	14.5	4.3	70	13.5	2.8	79	8.5	4.2	51
B	0.42	0.38	10	0.35	0.25	29	0.36	0.35	3
Ba	0.130	0.080	38	0.110	0.080	27	0.125	0.040	68
Be*	--	--	--	--	--	--	0.010	0.010	0
Ca	40.0	138.0	-245	64.5	94.0	- 46	56.0	64.0	- 14
Cd*	10.0	7.0	30	11.5	3.0	74	11.0	3.0	73
Co	0.040	0.050	- 25	0.051	0.059	- 16	0.024	0.017	29
Cr	0.190	0.010	95	0.090	0.005	94	0.215	0.012	94
Cu	0.069	0.026	62	0.121	0.040	67	0.30	0.030	90
Fe	1.00	0.050	95	0.80	0.20	75	1.17	0.08	93
Hg*	0.50	0.04	92	0.26	0.03	88	0.36	0.011	69
K	14.9	14.3	4	--	--	--	12.8	12.0	6
Mg	5.21	0.37	93	5.25	2.37	55	4.78	4.68	2
Mn	0.070	0.004	94	0.079	0.016	80	0.080	0.020	75
Mo*	2.0	2.0	0	--	--	--	13.0	2.5	81
Na	110.0	109.0	1	96.5	79.0	18	90.5	89.0	2
Ni	0.090	0.020	78	0.126	0.072	43	0.100	0.050	50
Pb	0.100	0.040	60	0.080	0.030	63	0.110	0.030	73
Se*	11.0	0.21	98	3.8	0.0	100	3.0	0.0	100
Si	9.0	--	--	9.4	7.8	17	9.8	10.8	- 10
Sr	0.26	0.28	- 8	0.88	0.65	26	--	--	--
V*	3.6	--	--	3.1	2.2	29	5.2	4.0	23
Zn	0.305	0.030	90	0.180	0.450	-150	0.320	0.055	83

Concentration in mg/l (* µg/l). --: Not Available

Boron

Boron was very refractory to all treatment processes, and no significant statement can be made except that it was not removed.

Barium

The removal of barium was quite variable ranging from 25 to 58 percent for means and 27 to 68 percent for medians. As indicated in Figure 64 the activated sludge process was responsible for most of the barium reduction, with the AWT processes being rather ineffective.

Beryllium

Beryllium was present at concentrations too low to permit evaluation during this project.

Calcium

Calcium was added in the form of calcium hydroxide during all three phases of the project; therefore, the calcium concentration was increased in all three phases as a result of the lime feed.

Cadmium

Cadmium removal was generally good, with both the activated sludge and AWT processes contributing to its removal as shown in Figure 65. Cadmium was removed most effectively by lime and recarbonation sequence; 78 percent by medians. These removals were the result of both the activated sludge and AWT processes.

Cobalt

Cobalt was removed only slightly by the activated sludge process, and the data indicate slight removal during alum treatment; however, the change in mean concentration was only 0.004 mg/l. Cobalt was added by the treatment chemicals during both sequences involving lime as the primary coagulant.

Chromium

Chromium removals were excellent as Figure 66 indicates. The lime coagulation used in Phase I resulted in the greatest removal (95 percent by medians), but lime and recarbonation resulted in the lowest median concentration of 0.005 mg/l. It should be noted that most of the removal occurred in the biological process.

Copper

The data in Figure 67 clearly indicate that the activated sludge process was effective in removing copper and that the AWT processes investigated were not effective.

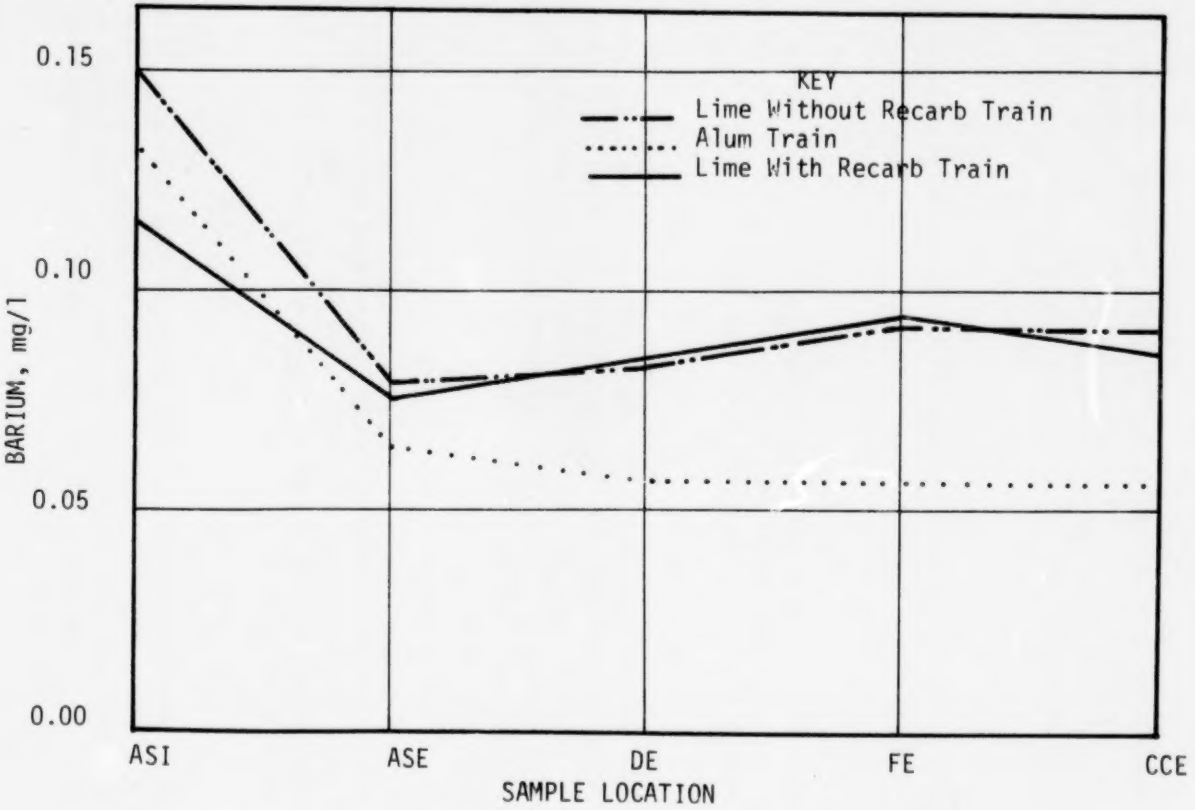

Figure 64. Barium concentration in wastewater after treatment by secondary and teritary processes.

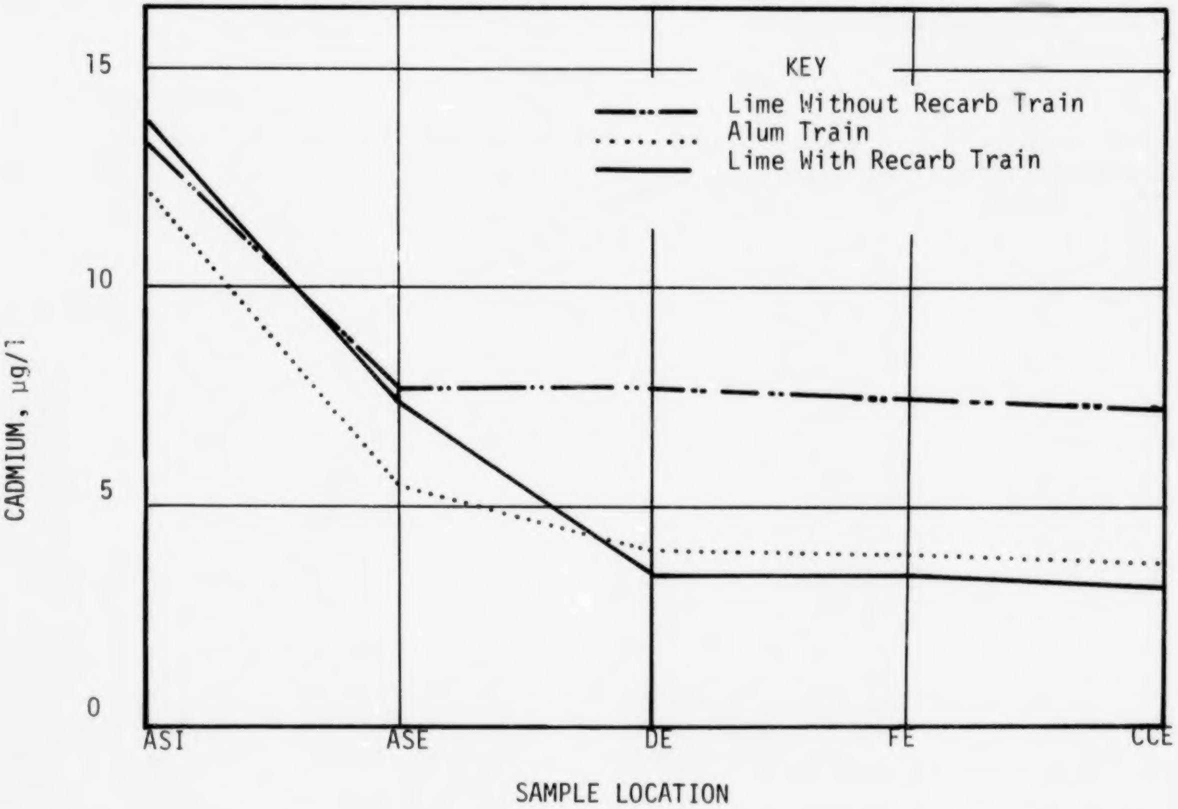

Figure 65. Cadmium concentrations remaining in wastewater after treatment by secondary and tertiary processes.

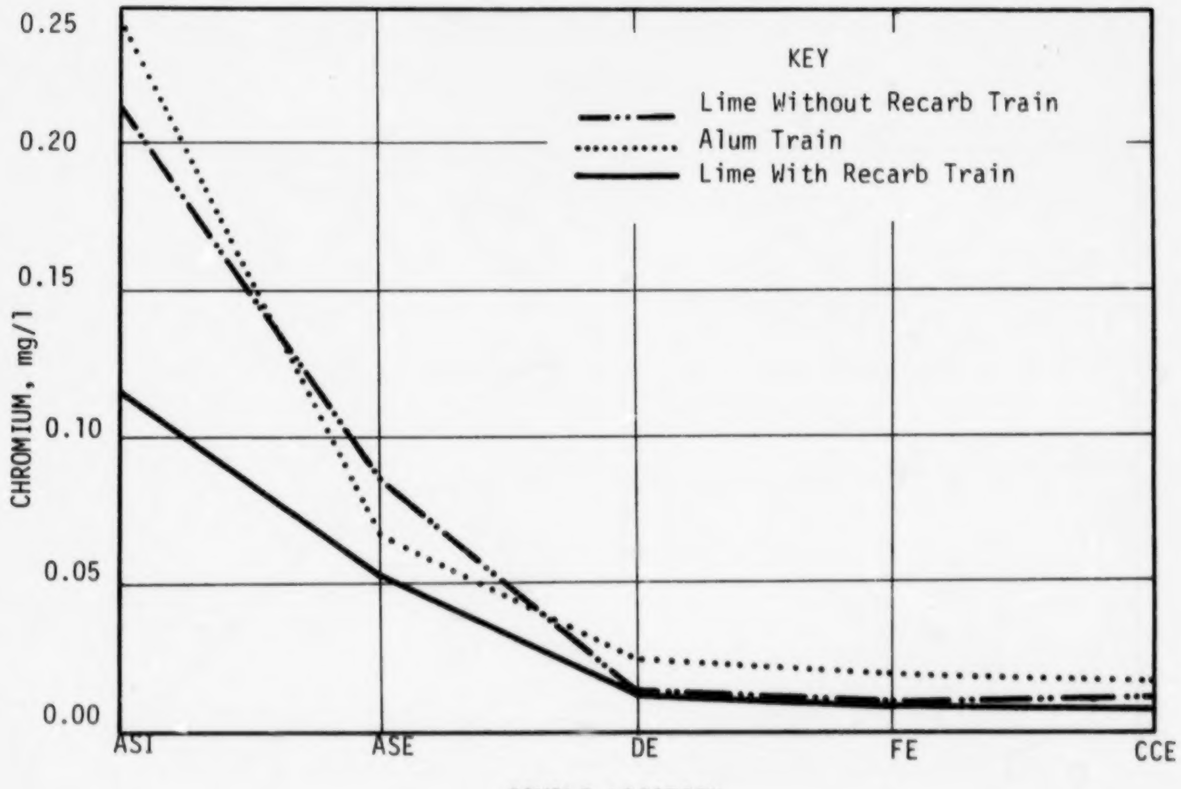

Figure 66. Chromium concentrations remaining in wastewater after treatment by secondary and tertiary processes.

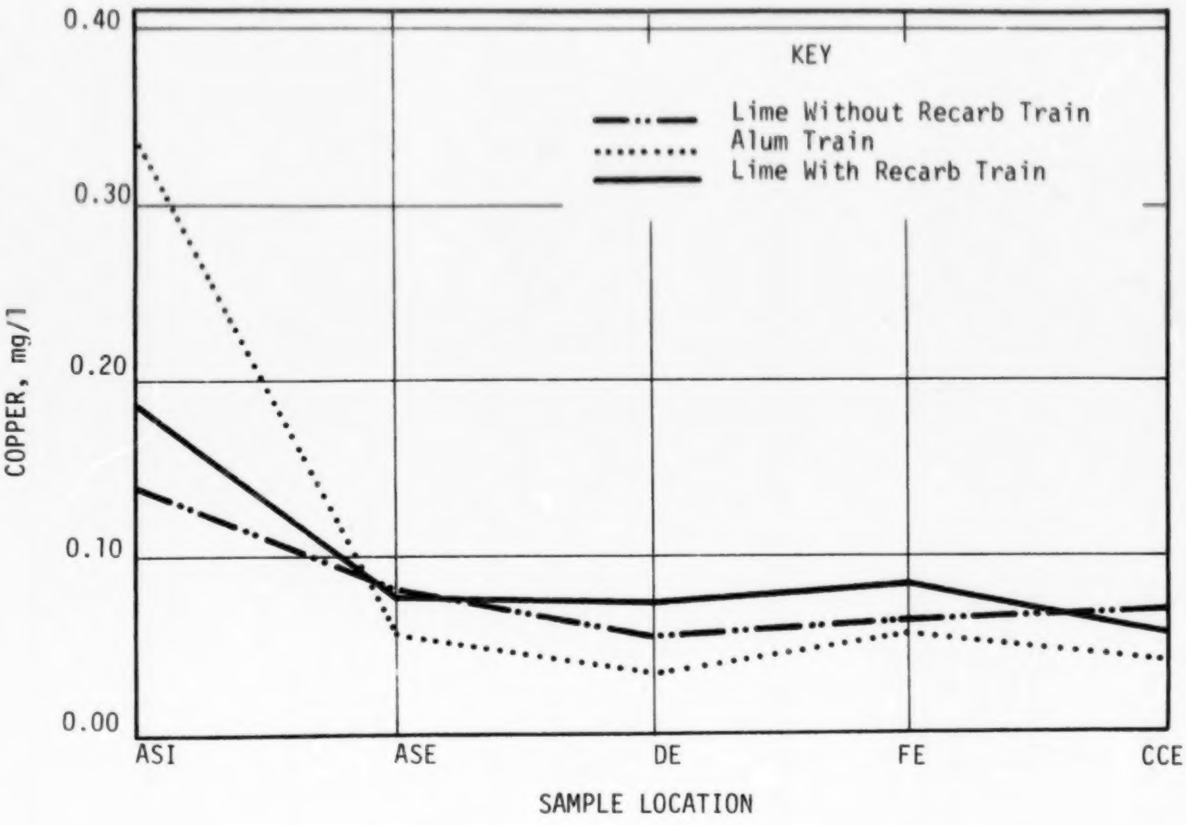

Figure 67. Copper concentrations remaining in wastewater after treatment by secondary and tertiary processes.

Iron

All of the treatment processes investigated were effective in removing iron. The peak in the lime and recarbonation curve shown in Figure 68 resulted from ferric chloride feed to the aeration basin of the activated sludge process. The high-pH lime coagulation train was the most effective treatment sequence for removing iron, achieving 94 percent by means and 95 percent by medians.

Mercury

Figure 69 showns the mean mercury concentrations at different points in the treatment sequence for all three sequences studied. The high-pH lime coagulation sequence resulted in the best removals of 79 percent by means and 92 percent by medians. The lime and recarbonation train resulted in the lowest concentrations of 0.08 mg/l by means and 0.03 mg/l by medians.

Potassium

No significant potassium removal was observed in any process.

Magnesium

Magnesium was removed by the two treatment sequences utilizing high-pH lime coagulation. Alum treatment was totally ineffective for removing magnesium. The best magnesium removal (93 percent by medians) occurred during the lime-only sequence; however, some difficulty was experienced during the lime and recarbonation phase in maintaining the pH at or above 11.0 due to a shipment of low quality lime. One would expect both processes to be equally effective in magnesium removal.

Manganese

As shown in Figure 70 both treatment sequences employing high-pH lime coagulation were effective in removing manganese, as was the activated sludge system. The lime coagulation only sequence resulted in the greatest removal (94 percent by medians) and the lowest concentration (0.004 mg/l by medians).

Molybdenum

No significant removal of molybdenum was observed.

Sodium

No significant removal of sodium was observed.

Nickel

Nickel removals were largest in the lime sequence, 72 percent by means and 78 percent by medians. The activated sludge process removed

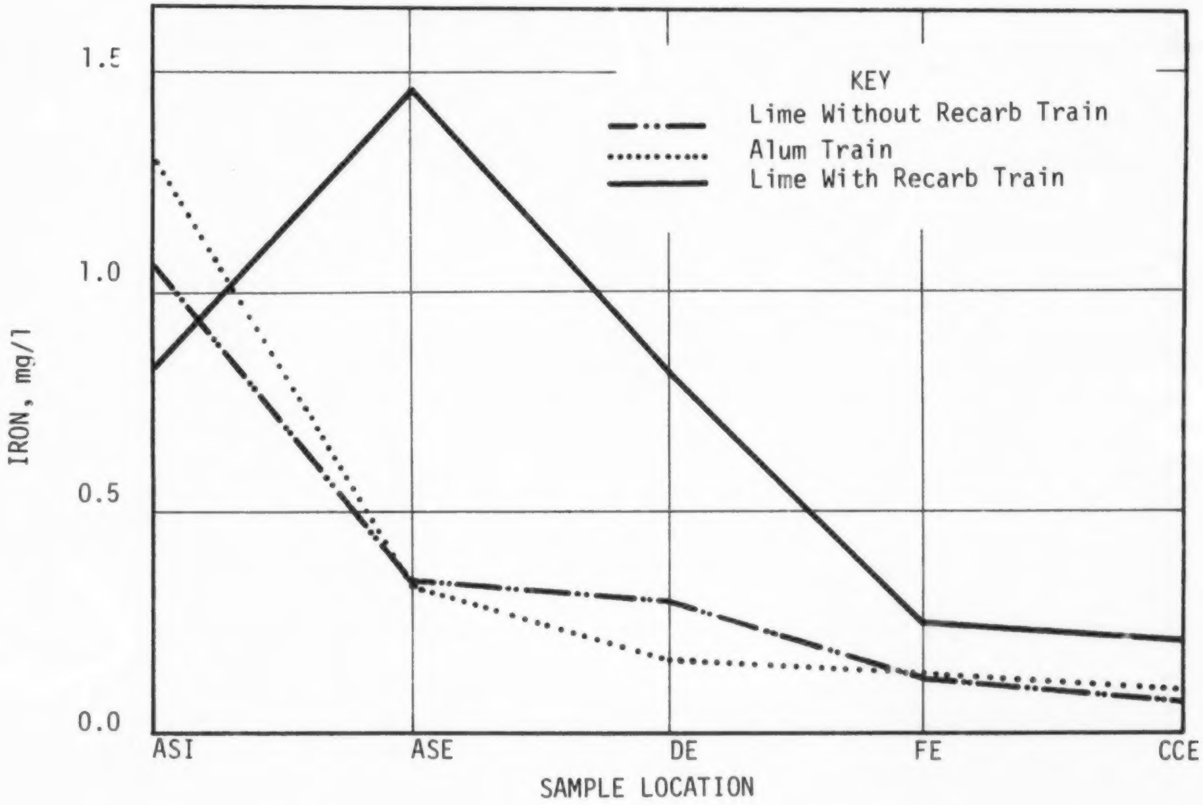

Figure 68. Iron concentrations remaining in wastewater after treatment by secondary and tertiary processes.

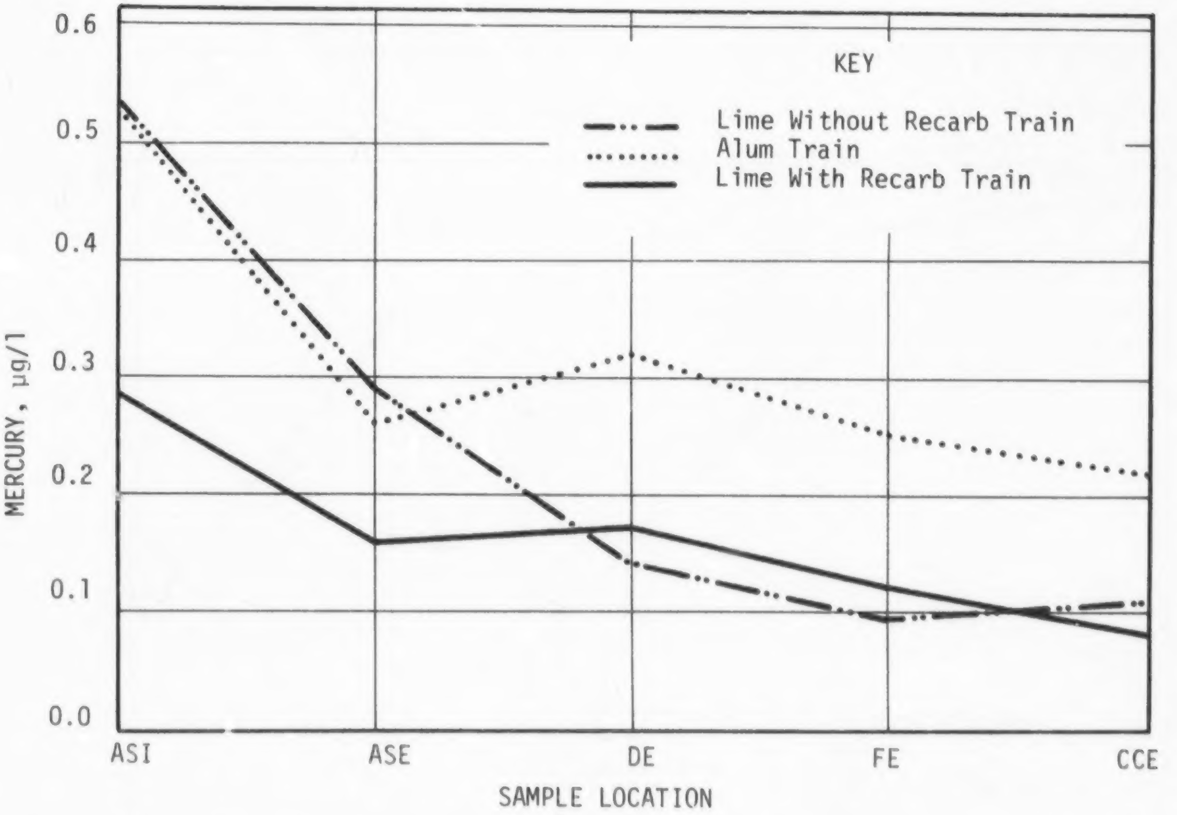

Figure 69. Mercury concentrations remaining in wastewater after treatment by secondary and tertiary processes.

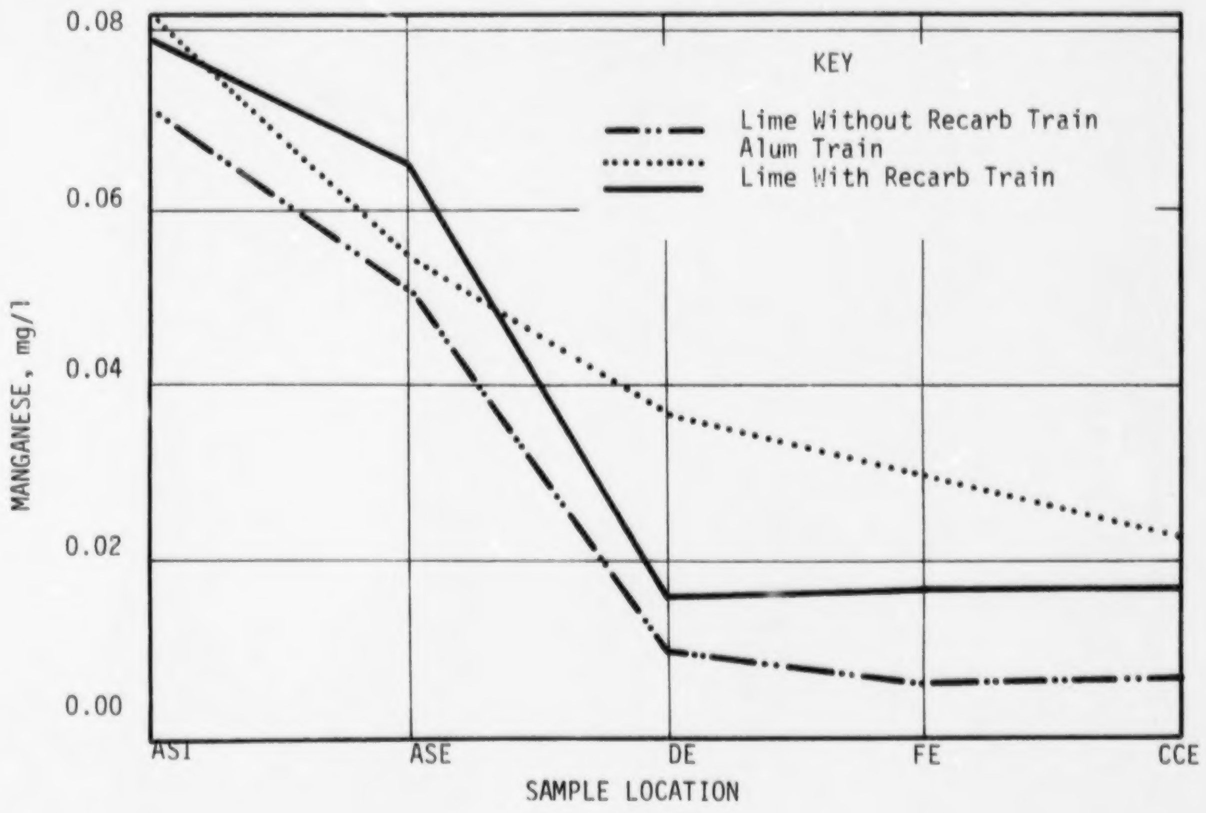

Figure 70. Manganese concentrations remaining in wastewater after treatment by secondary and tertiary processes.

a significant amount of nickle in all three treatment sequences studied.

Lead

Lead removal was good, generally averaging 60 to 70 percent. The data shown in Figure 71 indicate that all three treatment sequences performed approximately the same, with the lime and recarbonation phase having a slight edge. The activated sludge process was an important contributor to lead removal in all three sequences.

Selenium

As indicated in Figure 72, selenium removals were excellent for all three treatment sequences. When the median concentrations are evaluated no selenium was present in the effluents from the alum and the lime and recarbonation sequences.

Silicon

No truly significant changes in silicon concentrations were observed during this project.

Strontium

The lime and recarbonation sequence made the most significant reduction in strontium concentration, 19 percent by means and 26 percent by medians.

Vanadium

The high-pH sequences were relatively effective in reducing the vanadium concentration, with 41 percent (by mean) being the best (lime and recarbonation). The maximum change in mean concentration was 1.4 mg/l.

Zinc

As shown in Figure 73 zinc removals were excellent except for the recarbonation study. The zinc from the galvanizing was solubilized by the carbonic acid which resulted in the obvious increases. All unit processes were effective in removing zinc to some degree, and an overall removal of 85 to 90 percent is a reasonable estimate of the treatment sequence performance.

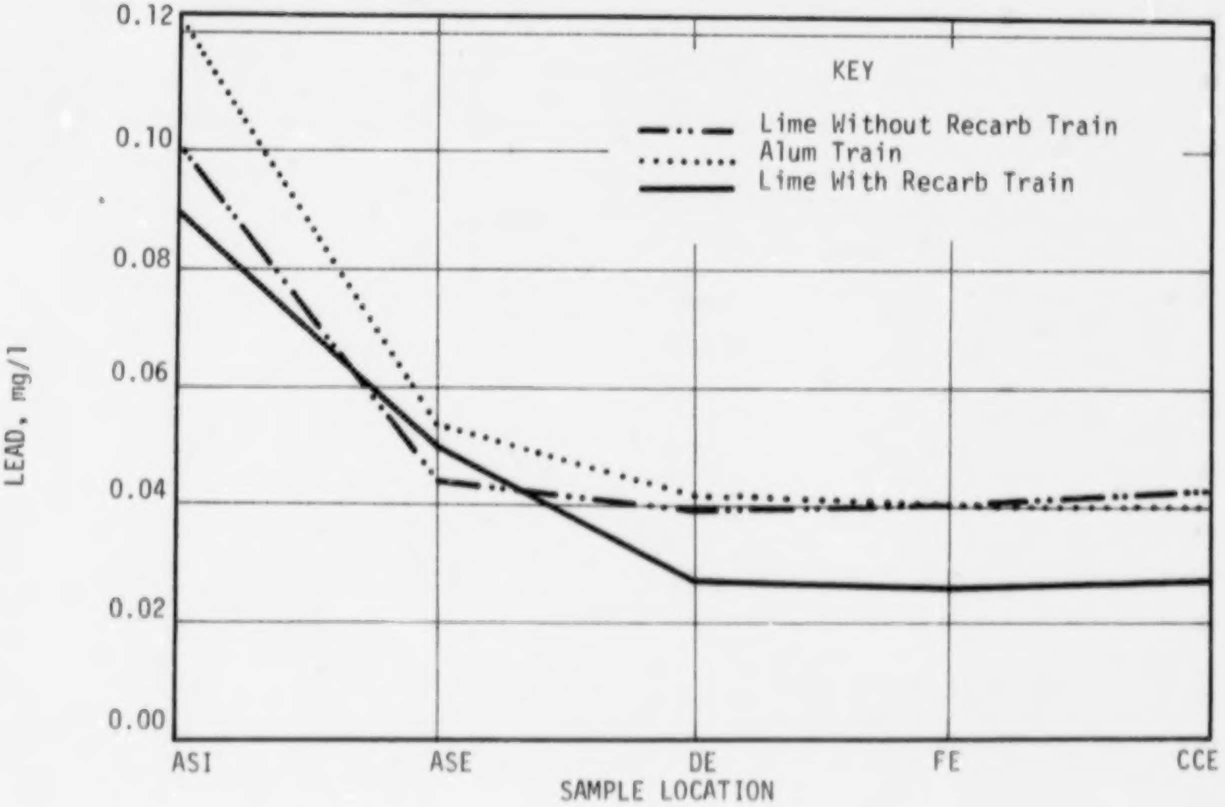

Figure 71. Lead concentration remaining in wastewater after treatment by secondary and tertiary processes.

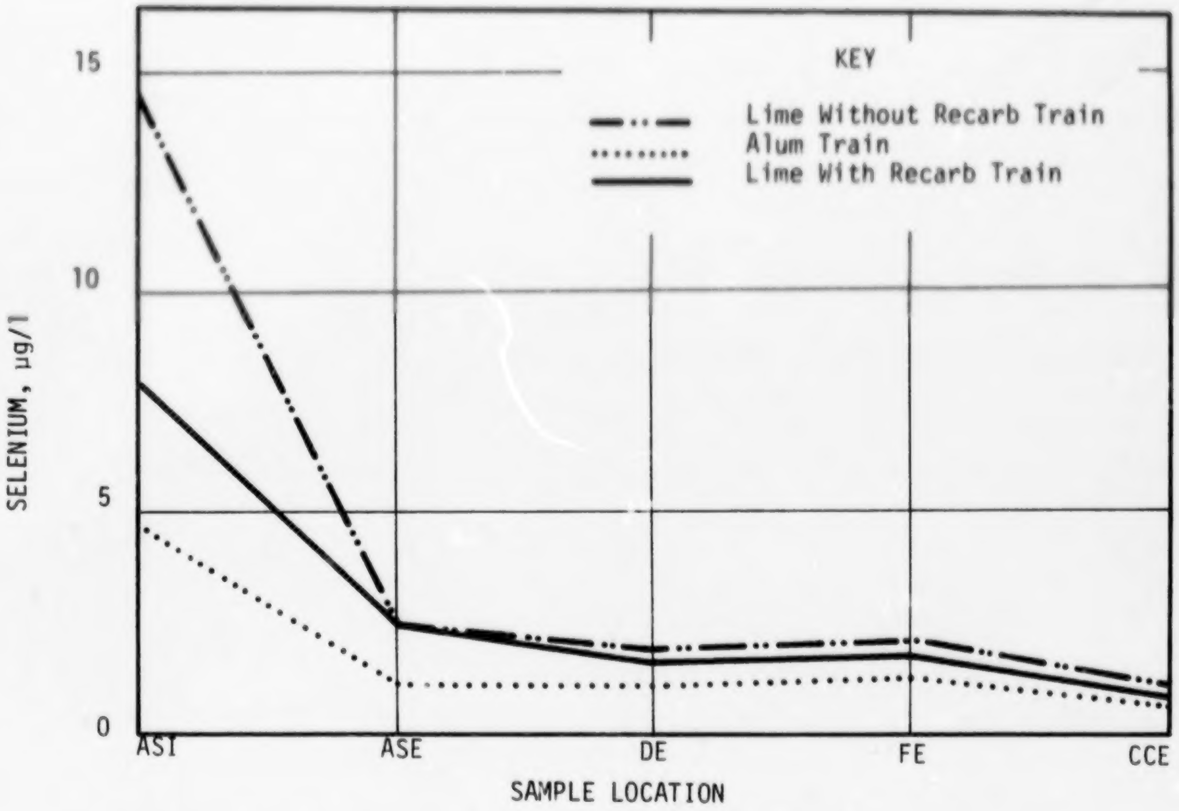

Figure 72. Selenium concentrations remaining in wastewater after treatment by secondary and tertiary processes.

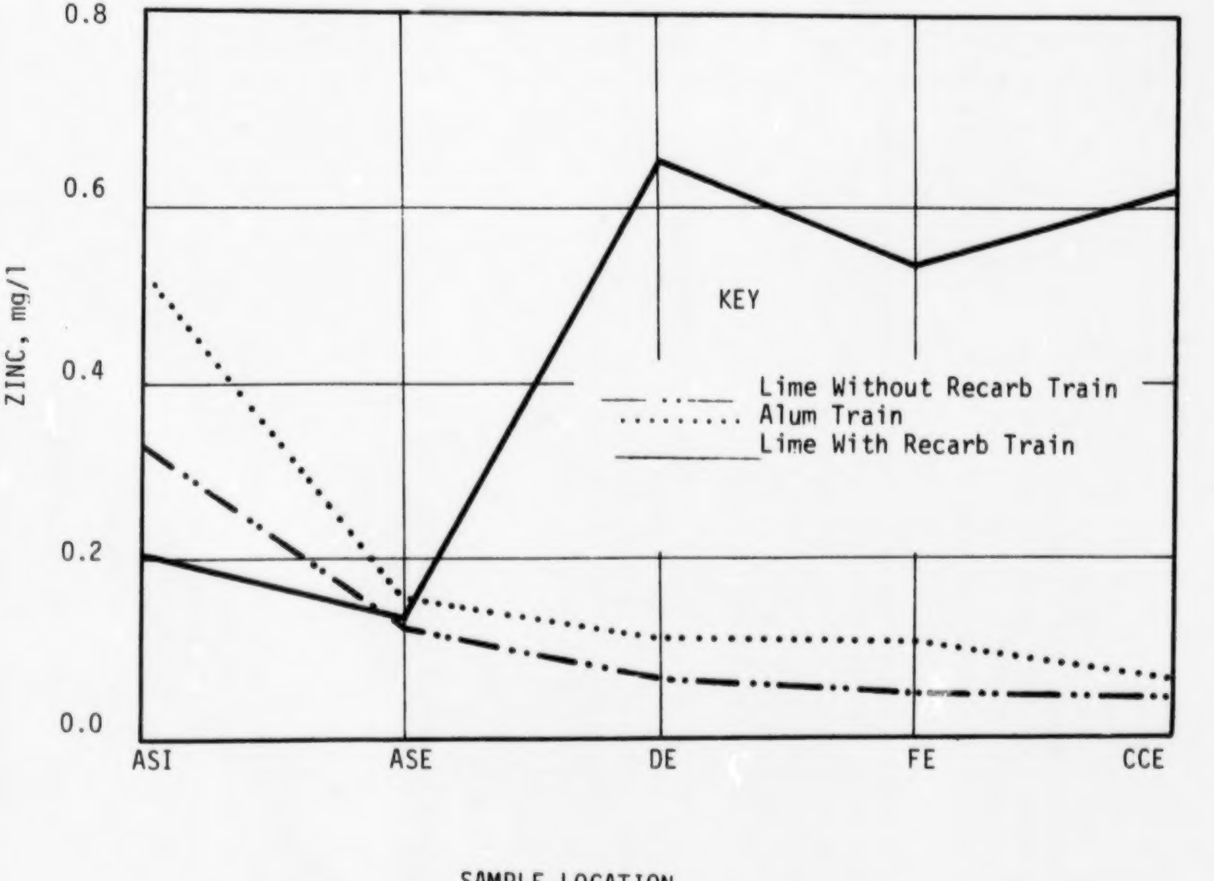

Figure 73. Zinc concentrations remaining in wastewater after treatment by secondary and tertiary processes.

METALS REMOVAL SUMMARY

This research effort generated an exhaustive amount of data which are relevant to the metals removals that can be obtained from AWT processes, and it is quite impossible to present an indepth data analysis in any single document. Many factors such as nitrification, the influent concentration of the metal, pH, coagulant dose, and product water turbidity can have a pronounced effect on the removal of a given metal in any given treatment system. Additionally, the data can be presented in terms of arithmetic means, geometric means, medians, modes, etc. Conventional practice is to report arithmetic means, since most effluent limitations are based on arithmetic means, and that practice was followed in this report to a considerable extent; however, in many cases significant differences exist between the arithmetic mean, the geometric mean, and the median concentration observed.

Table 63 presents the observed changes in mean metals concentrations that resulted from the chemical treatment process utilized during the three phases of the research effort. The reasons for increases in calcium, barium, cobalt, and zinc have been previously discussed. In almost every instance the absolute value of the change in concentration was very small, while the percent removal (or increase) was often substantial.

Data relevant to percent metals removal by chemical treatment are shown in Table 64. Even though changes in concentration may be small, metals removals of about 40 percent and greater can be considered significant. These data indicate that the high-pH lime coagulation processes are generally more effective for removing metals. This is especially true of the toxic metals such as arsenic, cadmium, chromium, mercury, and lead. In addition, the removal of both calcium and zinc would have been greatly enhanced with proper two-stage recarbonation facilities.

Evaluation of metals removals by the filtration processes does provide some meaningful insight as to whether the metal was in a soluble form or in the solids carried over from the upflow clarifier. Table 65 presents the changes in metals concentrations that resulted from filtration, and Table 66 shows the percent metals removal effected by the filters. The very slight increase in copper concentration is most probably an indication of copper pick-up from piping appurtenances such as bronze valve seats, etc. The other increases are slight. In this respect aluminum is a good example. The data in Table 66 indicate increases in aluminum concentrations of 45 percent for Phase 1 and 40 percent for Phase 2. However, the data in Table 67 indicate increases in the aluminum concentration of 0.09 mg/l and 0.06 mg/l for Phases 1 and 3, respectively. These increases are so slight that one must conclude no significant change in aluminum concentration resulted from filtration.

Tables 67 and 68 present the observed changes in metals concentrations and corresponding percent removals as a result of both chemical treatment and filtration. These data have been evaluated with respect to both percent

TABLE 53. CHANGE IN MEAN METALS CONCENTRATIONS BY CHEMICAL TREATMENT

METAL	PHASE 1 (mg/l)	PHASE 2 (mg/l)	PHASE 3 (mg/l)
Ag*	+0.68	0.0	--
Al	0.18	+1.71	0.32
As*	8.7	3.3	16.7
B	0.01	+0.02	0.02
Ba	+0.004	0.008	+0.009
Be*	--	0.0045	--
Ca	+113.6	+13.6	+41.2
Cd*	0.0	1.5	3.9
Co	+0.021	+0.001	+0.019
Cr	0.073	0.043	0.041
Cu	0.052	0.020	0.004
Fe	0.04	0.17	0.63
Hg*	0.15	+0.06	0.09
K	+0.2	0.2	--
Mg	3.98	0.09	2.56
Mn	0.041	0.018	0.05
Mo*	+2.1	1.1	--
Na	+9.2	+0.1	0.3
Ni	0.030	0.011	0.023
Pb	0.005	0.012	0.023
Se*	0.5	0.1	0.9
Si	+3.8	+0.7	1.2
Sr	0.01	--	0.08
V*	0.6	0.3	+0.3
Zn	0.06	0.047	+0.521

*Concentration in micrograms per liter

+ indicates observed concentration increased

-- Not Available

TABLE 64. PERCENT METALS REMOVAL BY CHEMICAL TREATMENT

	..................Percent Removal	....	
METAL	PHASE 1	PHASE 2	PHASE 3
Ag	+261.5	0.0	--
Al	47.4	+407.1	68.1
As	44.6	32.7	81.1
B	2.4	+5.7	5.6
Ba	+5.1	12.3	+12.0
Be	--	90.0	--
Ca	+267.3	+24.4	+63.5
Cd	0	26.8	53.4
Co	+56.8	+3.8	+39.6
Cr	85.9	65.2	78.8
Cu	30.0	37.0	5.2
Fe	11.8	51.5	43.4
Hg	51.7	+23.1	34.6
K	+1.4	1.6	--
Mg	80.1	1.9	51.6
Mn	80.4	32.7	75.8
Mo	+100.0	26.2	--
Na	+8.5	+0.1	0.3
Ni	36.6	13.9	21.7
Pb	11.4	22.2	46.0
Se	20.1	9.1	37.5
Si	+39.6	+7.2	12.9
Sr	4.2	--	11.1
V	14.3	7.1	+10.3
Zn	48.8	30.1	+391.7

+ Indicates observed concentration increased

-- Not Available

TABLE 65. CHANGE IN MEAN METALS CONCENTRATIONS BY FILTRATION

METAL	PHASE 1 (mg/l)	PHASE 2 (mg/l)	PHASE 3 (mg/l)
Ag*	0.0	0.0	--
Al	+0.09	1.35	+0.06
As*	3.8	0.7	0.4
B	0.0	+0.01	+0.02
Ba	+0.009	0.001	+0.01
Be	--	+0.0115	--
Ca	0.0	0.8	9.6
Cd	0.2	0.1	0.1
Co	0.001	0.0	0.005
Cr	0.003	0.004	0.003
Cu	+0.1	+0.022	+0.009
Fe	0.18	0.03	0.58
Hg*	0.046	0.07	0.05
K	+0.2	0.2	--
Mg	0.33	+0.07	+0.21
Mn	0.0039	0.007	+0.001
Mo*	2.5	+0.7	--
Na	0.2	0.4	7.5
Ni	0.1	+0.002	0.011
Pb	+0.001	0.002	0.001
Se*	+0.14	+0.2	+0.2
Si	6.7	0.7	0.5
Sr	0.0	--	+0.02
V*	1.2	+0.1	+0.4
Zn	0.015	0.003	0.122

* Concentration in micrograms per liter

+ Indicates the observed metal concentration increased

-- Not Available

TABLE 66. PERCENT METALS REMOVAL BY FILTRATION

	.............Percent Removal		....
METAL	PAHSE 1	PHASE 2	PHASE 3
Ag	0.0	0.0	--
Al	+45.0	63.4	+40.0
As	35.2	10.3	10.3
B	0.00	+2.7	+5.9
Ba	+10.8	1.8	+11.9
Be	--	+2300.	--
Ca	0.00	1.2	9.0
Cd	2.7	2.4	2.9
Co	1.72	0.00	7.5
Cr	25.0	17.4	27.3
Cu	+17.9	+64.7	+12.3
Fe	60.0	18.8	70.8
Hg	32.9	21.9	29.4
K	+1.4	1.6	--
Mg	33.3	+1.5	+8.8
Mn	39.0	18.9	+6.3
Mo	59.6	+22.6	--
Na	0.17	0.45	8.3
Ni	19.2	+2.9	13.3
Pb	+2.6	4.8	3.7
Se	+7.4	+20.	+13.3
Si	50.0	6.7	6.2
Sr	0.00	--	+3.1
V	33.3	+2.6	+12.5
Zn	23.8	2.8	18.7

+ Indicates the observed concentration increased

-- Not Available

TABLE 67. CHANGE IN MEAN METALS CONCENTRATIONS BY CHEMICAL TREATMENT AND FILTRATION

METAL	PHASE 1	PHASE 2	PHASE 3
Ag*	+0.68	0.0	--
Al	0.09	+0.36	0.26
As*	12.5	4.0	17.1
B	0.01	+0.03	0.00
Ba	+0.015	0.009	+0.019
Be	--	+0.007	--
Ca	+113.6	+12.8	+31.6
Cd*	0.2	1.6	4.0
Co	+0.02	+0.001	+0.014
Cr	0.076	0.047	0.044
Cu	0.014	+0.002	+0.005
Fe	0.22	0.20	1.21
Hg*	0.196	0.01	0.14
K	+0.4	0.40	--
Mg	4.31	0.02	2.35
Mn	0.0449	0.025	0.049
Mo*	0.4	0.4	--
Na	+9.0	0.3	7.8
Ni	0.04	0.009	0.34
Pb	0.004	0.014	0.024
Se*	0.36	+0.1	0.7
Si	2.9	0.00	1.7
Sr	0.01	--	0.06
V*	1.8	0.2	+0.7
Zn	0.075	0.05	+0.399

* Concentration in micrograms per liter

+ Indicates the observed concentration increased
-- Not Available

TABLE 68. PERCENT METALS REMOVAL BY CHEMICAL TREATMENT AND FILTRATION

	...........Percent Removal	....	
METAL	PHASE 1	PHASE 2	PHASE 3
Ag	+261.5	0.00	--
Al	23.7	+85.7	55.3
As	64.1	39.6	83.0
B	2.4	+8.6	0.00
Ba	+16.5	13.8	+25.3
Be	--	+140.0	--
Ca	+267.3	+22.9	+48.7
Cd	2.6	28.6	54.8
Co	+54.1	+3.8	+29.2
Cr	89.4	71.2	84.6
Cu	17.5	+3.7	+6.5
Fe	64.7	60.6	83.4
Hg	67.6	3.8	53.8
K	+2.8	3.1	--
Mg	86.7	0.43	47.4
Mn	88.0	45.4	74.2
Mo	19.0	9.5	--
Na	+8.3	0.34	8.6
Ni	48.8	11.4	32.1
Pb	9.1	25.9	48.0
Se	15.0	+9.1	29.2
Si	30.2	0.00	18.3
Sr	4.2	--	8.3
V	42.9	4.8	+24.1
Zn	61.0	32.1	+300.0

+ Indicates observed concentration increased

-- Not Available

removal and change in concentration, such that Table 69 could be presented.

Tables 72 and 74 present data for metals removals by the activated carbon adsorption process. In all cases the absolute change in concentration was small. The carbon columns served as good filters; therefore those metals which formed precipitates as a result of coagulation were removed to some extent. Iron, mercury, and copper to a lesser extent, are typical examples of this removal.

The carbon columns were effective in reducing the selenium concentration by at least fifty percent in all three phases of the study. Significant vanadium removals (20 to 44 percent) were observed in the carbon columns when high-pH treatment was employed.

The changes in the mean metals concentrations, and the removals obtained by the AWT processes, are presented in Table 72. These data represent differences between the activated sludge effluent and the effluent from the activated carbon columns. The AWT processes were effective in removing arsenic, cadmium, chromium, copper, iron, mercury, magnesium, manganese, nickel, selenium, vanadium, zinc, and to a lesser extent lead. The other metals studied during this project were essentially unaffected by the AWT processes used.

In any facility being used for potable reuse it will probably be totally impractical to monitor the concentrations of twenty-plus individual metals on a continuous basis. In many instances the time required for analysis of a given metal is several tens of hours; therefore, one of the major objectives of this research effort that was shared by all members of the staff, was the development of parametric relationships that could be used to predict the removal of specific metals, without actually analyzing for the specific metal.

Tables 73 through 75 present the results of some of the efforts at parametric correlation. In these studies linear regressions for every metal were computed as a function of the other individual metals. The linear correlation analyses were performed for each metal at every point in the treatment sequence. Under each column, which represents a specific sampling point, the individual metal-metal correlations with a correlation coefficient greater than $|0.80|$ are listed, along with the number of paired data points used for the correlation.

When evaluating these tables it is obvious that the more significant correlations exist in the lower-quality wastewaters, which could be anticipated due to the improved analytical accuracy.

Tables 73 and 75 indicate that aluminum is a good indicator for a number of other metals, including mercury, cadmium, strontium, and chromium. Table 74 strongly suggests that beryllium should be a good indicator for chromium, iron manganese, nickle, and lead.

TABLE 69. SUMMARY OF METALS REMOVAL DEMONSTRATED BY CHEMICAL TREATMENT AND FILTRATION PROCESSES

OBSERVED PERFORMANCE	HIGH-pH LIME COAGULATION AND RECARBONATION	ALUM COAGULATION
Significant Removals Observed	Al As Cd Cr Fe Hg Mg Mn Ni Pb Zn Se	As Cr Fe Mn Pb Zn
No Significant Removal Observed	B Ba Cu K Mo Na Si Sr V	B Ba Cu K Mo Na Ni Si Sr V

TABLE 70. CHANGE IN MEAN METAL CONCENTRATION BY ACTIVATED CARBON ADSORPTION

METAL	PHASE 1 (mg/l)	PHASE 2 (mg/l)	PHASE 3 (mg/l)
Ag*	0.32	0.0	--
Al	+0.07	0.18	0.05
As*	0.6	0.3	0.0
B	0.02	0.03	0.04
Ba	0.001	0.0	0.008
Be*	-	0.002	-
Ca	11.2	2.4	+4.7
Cd*	0.2	0.2	0.3
Co	0.003	0.002	+0.001
Cr	+0.0005	0.003	0.002
Cu	+0.005	0.017	0.028
Fe	0.056	0.04	0.04
Hg*	+0.016	0.03	0.04
K	0.2	0.7	--
Mg	0.08	0.1	0.15
Mn	+0.0006	0.007	0.0
Mo*	+0.2	0.6	--
Na	+0.4	2.5	0.8
Ni	0.013	0.012	+0.006
Pb	+0.003	0.0	+0.001
Se*	1.04	0.6	1.0
Si	+2.1	+0.2	0.3
Sr	0.0	--	0.02
V*	+0.5	+0.3	1.6
Zn	0.007	0.039	+0.085

* micrograms per liter

-- no data available

+ increase in concentration

TABLE 71. PERCENT METALS REMOVAL BY ACTIVATED CARBON ADSORPTION

	Percent Removal		
METAL	PHASE 1	PHASE 2	PHASE 3
Ag	34.0	0.0	--
Al	+24.1	23.1	23.8
As	8.6	4.9	0.0
B	4.9	7.9	11.1
Ba	1.1	0.0	8.5
Be	--	16.7	-
Ca	7.2	3.5	+ 4.9
Cd	2.7	5.0	9.1
Co	5.3	7.4	+ 1.6
Cr	+ 5.5	15.8	25.0
Cu	+ 7.6	30.4	34.1
Fe	46.7	30.8	16.7
Hg	+17.0	12.0	33.3
K	1.4	5.7	-
Mg	12.1	2.1	5.7
Mn	+ 9.8	23.3	0.0
Mo	+11.8	15.8	--
Na	+ 0.3	2.8	0.9
Ni	30.1	17.1	+ 8.3
Pb	7.5	0.0	+ 3.8
Se	51.0	50.0	58.8
Si	+31.3	+ 2.1	3.9
Sr	0.0	--	3.0
V	+20.8	+ 7.5	44.4
Zn	14.6	36.8	+16.0

-- no data available

+ increase

TABLE 72. CHANGE IN MEAN METAL CONCENTRATION AND PERCENT REMOVAL FOR THE AWT PROCESSES

METAL	PHASE 1		PHASE 2		PHASE 3	
	mg/l	(%)	mg/l	(%)	mg/l	(%)
Ag*	+ 0.36	(+138)	0.0	(0.0)	--	(--)
Al	0.02	(5.3)	+ 0.18	(+42.9)	0.31	(66.0)
As*	13.1	(67.2)	4.3	(46.6)	17.1	(83.0)
B	0.02	(4.8)	0.0	(0.0)	0.04	(11.1)
Ba	+ 0.012	(+15.2)	0.009	(13.8)	+ 0.011	(+14.7)
Be	-	(--)	+ 0.005	(+100)	--	(--)
Ca	+102.4	(+241)	+10.4	(+18.6)	+36.3	(+55.9)
Cd	0.4	(5.3)	1.8	(32.1)	4.3	(58.9)
Co	+ 0.017	(+45.9)	0.001	(3.8)	+ 0.015	(+31.2)
Cr	0.076	(88.8)	0.05	(75.8)	0.046	(88.5)
Cu	0.009	(11.3)	0.015	(27.8)	0.023	(29.9)
Fe	0.28	(81.2)	0.24	(72.7)	1.25	(88.2)
Hg*	0.18	(62.1)	0.04	(15.4)	0.18	(69.2)
K	+ 0.2	(+ 1.4)	1.1	(8.7)	--	(--)
Mg	4.39	(88.3)	0.12	(2.6)	2.5	(50.4)
Mn	0.044	(86.9)	0.032	(58.2)	0.049	(74.2)
Mo*	0.2	(9.5)	1.0	(23.8)	--	(--)
Na	+ 9.4	(+8.7)	2.8	(3.1)	8.6	(9.5)
Ni	0.053	(64.6)	0.021	(26.6)	0.028	(26.4)
Pb	0.001	(2.3)	0.014	(25.9)	0.023	(46.0)
Se*	1.4	(58.3)	0.5	(45.4)	1.7	(70.8)
Si	0.8	(8.3)	+ 0.2	(+ 2.1)	2.0	(21.5)
Sr	0.01	(4.2)	--	(--)	0.08	(11.1)
V*	1.3	(30.9)	+ 0.1	(+ 2.4)	0.9	(31.0)
Zn	0.082	(66.7)	0.089	(57.1)	+0.484	(+370)

* micrograms per liter

+ increase in concentration

-- no data available

TABLE 73. METALS CONCENTRATIONS HAVING LINEAR CORRELATION COEFFICIENTS (r) OF 0.80 OR GREATER, HIGH-pH LIME TREATMENT WITHOUT RECARBONATION

A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	FILTER EFFLUENT**	CARBON EFFLUENT**
Al, Ba,6*	Al, Cd,6*	Al, Ba,4(I)	Cu,Zn,60*	NONE
Al, Cr,6*	Al, Ca,6	Al, Ca,4	Mo, Pb,9	
Al, Fe,6*	Al, Hg,4*	Al, Cd,4		
Al, Ni,6*	Al, Sr,4	Al, Co,4*		
Al, Pb, 6	Ca, Sr,6	Al, Ni,4		
Al, Sr,4(I)	Co, Sr,6	Al, Pb,4		
Mn, Mo,10	Cr,Pb,65	As, V,4		
Si, V,4	Cu, Zn,66	Ca, Sr,4*		
	Na, Si,6	Cd, Sr,4		
	Si, Sr,4	Co, Sr,4		
	Si, V,4*	Na, Si,4*		

* $0.90 \leq r < 1.00$

** Insufficient data for correlations involving Al, Si, Sr, V

(I) Inverse, or negative, correlation

TABLE 74. METALS CONCENTRATIONS HAVING LINEAR CORRELATION COEFFICIENTS (r) OF 0.80 OR GREATER; ALUM TREATMENT

A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	FILTER EFFLUENT	CARBON EFFLUENT
B, K,9	Al, Mo,7*	Al, Be,18*	As, Be,5	B, Mg,7*
B, Mg,9	Hg, Si,11	Be, Cr,19	B, Mg,8	Be, Cr,4*
Be, V,10(I)	K, Na,9	Be, Fe,11	Be, Cr,5	K, Na,7*
Cu, K,9*	Pb, Si,12	Cd, K,9	Be, Mn,4(I)	
Hg, K,8*		K, Na,9	Be, Ni,4*	
Mg, Na,9			Be, Pb,5 (I)	

*$0.90 \leq r < 1.00$
(I) Inverse, or negative, correlation

TABLE 75. METALS CONCENTRATIONS HAVING LINEAR CORRELATION COEFFICIENTS (r) OF 0.80 OR GREATER, HIGH-pH LIME TREATMENT WITH RECARBONATION

A.S. INFLUENT	A.S. EFFLUENT	DENSATOR EFFLUENT	RECARB EFFLUENT	FILTER EFFLUENT	CARBON EFFLUENT
Al, Fe, 41	Al, Cr,42	Fe, Mn,43	Fe, Mn,41	Na, Si,33	Cd, Co,33
Cr, Fe,44	Al, Cu,42				
	Al, Fe,42*				
	Al, Mn,42				
	Al, Pb,42				
	Cr, Fe,45				
	Cr, Mn,45				
	Cr, Pb, 46				
	Cu, Fe,45				
	Fe, Mn,45				
	Fe, Pb,44				
	Na, Si,42				

*$0.90 \leq r < 1.00$

The authors must emphasize the fact that the indirect parametric determination of any water quality parameter is subject to considerable debate. The metals data developed during this project are not sufficient to substantiate any definitive parametric correlations. One of the more important facts learned during this project was that it was totally impossible to predict the concentration of a specific metal at any given point in time and process.

The percent of the total samples in the influent and effluent to each of the three treatment sequences that exceeded the drinking water limits is presented in Table 76. Although when viewed in this manner the total number of metals which pose treatment problems are small, the metals that pose the problems all have demonstrated public health hazards. It should be noted that a metal that is present at the maximum contaminant level (MCL) one day per year has a recurrence percentage greater than 0.3 percent.

A summary of metals removals is presented in Table 77. When evaluated in terms of maximum effectiveness for removing metals the lime and recarbonation sequence would appear to be the most effective. These data were not obtained over the same time period, or over identical sampling intervals, which makes data evaluation most difficult.

The use of high-pH lime coagulation without recarbonation is very unlikely; therefore; this treatment process is not included in the summary. However, certain data from Phase 1 were utilized to predict the performance of the Phase 3 system. Zinc removals should be good in the recarbonation system, provided proper materials of construction are used. Also the magnesium removals observed during Phase 1 of the study should be typical of a Phase 3 system. During Phase 1 the upflow clarifier was operated at a pH of 11.5, which was sufficient to precipitate magnesium as a hydroxide. However, during Phase 3 the operating pH was 10.5; too low for excellent magnesium precipitation.

From the data presented one must conclude that high-pH lime coagulation and recarbonation is more effective in removing metals than is alum coagulation. These observations have been made after an extensive investigation of advanced wastewater treatment processes on wastewater from the City of Dallas, Texas, where the industrial component of the wastewater flow is about seventeen percent. Regional and/or geographical differences could alter the reported results substantially.

Table 78 may be the most significant approach to evaluating metals removal. In this table the concentration of each metal in the final product water from each treatment sequence is evaluated as a function of the maximum contaminant level (MCL).

When the data in the Table 78 are carefully evaluated the following facts cannot be escaped; arsenic, cadmium, iron, manganese, and lead represent potential problems of undefined magnitude.

TABLE 76. PERCENTAGE OF SAMPLES EXCEEDING DRINKING WATER LIMITS

			TRAIN					
			LIME ONLY		LIME + RECARB		ALUM	
METAL	LIMIT MG/L	TYPE*	INF	EFF	INF	EFF	INF	EFF
Ag	0.05	M	0	0	--	--	0	0
As	0.05	M	4	0	9	0	1	0
B	1.0	R	0	0	0	0	0	0
Ba	1.0	M	0	0	0	0	0	0
Cd	0.01	M	46	21	56	0	54	1
Cr	0.05	M	100	0	91	0	95	2
Cu	1.0	R	1	0	0	0	1	0
Fe	0.3	R	100	0	100	6	98	0
Hg	0.002	M	0	0	0	0	4	3
Mn	0.05	R	86	0	95	0	100	4
Pb	0.05	M	83	34	82	0	91	22
Se	0.01	M	52	0	35	0	11	0
Zn	5.0	R	0	0	0	0	0	0

* M= Maximum contaminant level, "Interim Primary Drinking Water Standards, "Federal Register, 40, 51 (March 14, 1975).

R= Recommended limit, EPA Secondary Regulations.

TABLE 77. COMPARISON OF OBSERVED METALS REMOVALS

Metal Removal (percent)	Phase 1 Lime	Phase 2 Alum	Phase 3 Lime and Recarbonation
90	Cr Fe Se Mn	Cr Fe	Cr Se
70 - 90	Mg Zn Hg	Zn Cu Se Mo Mn	As Mn Cd Al Fe Hg Pb Cu
50 - 70	As Al Ni Pb	Cd Pb Hg Ba	Mg
20 - 50	Cu Cd Ba V	As Ni Be	Ni V Ba Si
0 - 20	Sr Si Ag B	Co K V Na Mg Al Si B Ag	Sr Na B
Increase in Conc.	Na Co Ca	Ca	Co Ca Zn

TABLE 78. METALS CONCENTRATIONS IN AWT EFFLUENTS AS A PERCENT OF THE MAXIMUM RECOMMENDED CONCENTRATION

		Percent of Maximum Recommended Concentration		
Metal	MRC*	Lime	Alum	Lime and Recarbonation
Ag	0.05	1.2	0	--
As	0.01	64	58	35
B	1.0	39	35	32
Ba	1.0	0.9	5.6	8.6
Cd	0.01	72	38	30
Cr	0.05	19	32	12
Cu	1.0	7.1	3.9	5.4
Fe	0.3	21.3	30	66.7
Hg	0.002	5.5	11	4.0
Mn	0.05	13.4	46	34
Pb	0.05	86.0	84	52
Se	0.01	10	6	7
Zn	5.0	0.8	1.3	12.3

* Suggested by the most stringent value published (PEAW Standards).

SECTION 10

VIRUS INACTIVATION STUDY

GENERAL

Water supply research studies of virus removals in flocculation and settling processes indicated removals in the order of 95-99 percent(10, 11, 12). These studies were based primarily on the use of alum and included an observation that higher usage of chemicals increased the virus removal efficiency. Studies at the University of Illinois using bacteriophage showed 98 to 99.9 percent removals (13). These same studies were expanded to include wastewater and showed the effects of increasing concentrations of organics on depressing virus removal efficiencies. These data indicate that virus removals from wastewater by flocculation and settling processes can be expected to be in the lower range of the efficiencies cited above.

As far as lime flocculation is concerned, the first reports of the effects of high-pH lime treatment in destroying bacteria date back to the 1920's (14, 15). More recent and detailed observations of these effects by South African workers report marked differences in the response of gram-negative, gram-positive and acid-fast bacteria. The gram-negatives were the more susceptible, and the acid-fast were the more resistant, excepting the spores (16). The survival of only a relatively few gram-positive rods was precisely what was observed in Dallas, with the critical pH-contact time relationship appearing to exist in the range of pH of 11.2-11.3 and a time of 1.56 to 2.40 hours (17). Berg, et al. at the National Environmental Research Center (NERC) in Cincinnati extended the studies of lime flocculation and high pH to poliovirus type 1 and observed removals of 70 to 99.86 percent from innoculated secondary effluent, with higher removals occurring at higher pH's (18). When coupled with sand filtration, the removals increased to levels greater than 99.997 percent.

Operation of the Pilot Plant

An activated sludge effluent was processed in the upflow clarifier at a rate of 6.31 l/sec (100 gpm). The sludge blanket in the upflow clarifier was dropped to approximately the level of the flocculator outlet at the start of a run. The fluidizer bar was turned off, and no sludge was withdrawn or recycled during the run. A residence time distribution function study at this flow regime (Figure 74) showed that in spite of the 5 hour and 10 minute theoretical detention time, peak dye concentration in the effluent occurred two hours after the addition of a slug load. Nevertheless,

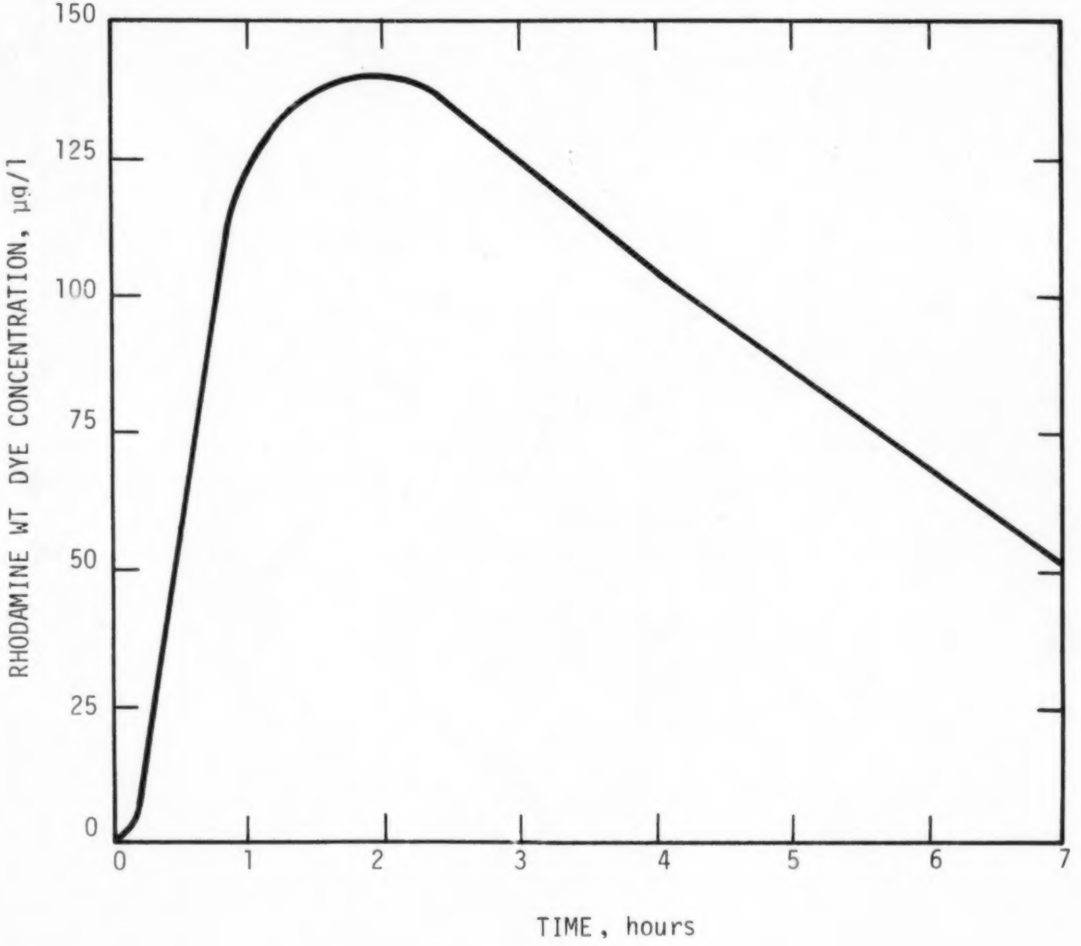

Figure 74. Residence time distribution function for the upflow clarifier.

seeding of the poliovirus-phage mixture continued for 10 hours to assure the achievement of a steady-state condition. The comparison of results obtained during the last five hours would then be used in determining separation efficiency.

The polioviruses were handled as though they were pathogenic organisms. The effluent from the upflow clarifier was directed to a chlorine contact basin where it was subjected to a dose of chlorine of 25 mg/l free residual for a period of 30 minutes, prior to discharge to the raw sewage of the White Rock Plant. It was believed that this treatment would destroy the viruses (19). The chlorine contact basin was sampled at different points to check on the virological performance of the disinfection process.

Immediately after the last sampling, the upflow clarifier was taken out of service. Chlorine was admitted to achieve a 40 mg/l free residual level, the fluidizer bar was turned on, the sludge recycle pump was turned on and the chlorine residual was maintained for 12 hours prior to dumping the contents to the raw wastewater inlet of the White Rock Plant. This treatment resulted in a bleached sludge, and it was hoped that this would destroy all the viruses. Sludge samples were taken before and after the chlorination process and assayed for disinfection performance.

RESULTS AND DISCUSSIONS OF THE VIRUS RUNS

Virus Run Number One

The frozen poliovirus stock was thawed in a water bath at 27°C. The thawed virus was aseptically divided into three gas-sterilized 18.9-liter Cubitainers each containing 18.5 liters of sterile distilled water. A quantity of f2 coliphage was added to each container to give a countable concentration in the effluent, assuming about 99 percent removal. One of the three Cubitainers was taken to the plant, immersed in an ice water bath, and fed into the suction of the pump feeding the upflow clarifier through a Gilmont No. 13 Flowmeter at 100 ml/min. The other two Cubitainers were stored in a refrigerator, and substituted in turn for the depleted containers with only momentary seeding disruptions. Each container was well agitated and sampled prior to the beginning of the seeding to check the diluted titer.

During this run the upflow clarifier was operated at a liquid alum feed concentration of 103 mg/l as the hydrated molecule. This was the lowest concentration that provided a visual appearance of a high quality water passing over the effluent weir. Turbidity as monitored by the Hach Continuous Flow Surface Scatter Trubidimeter on the day of the run averaged 0.3 units. The Al:P ratio was only 0.44.

Chemical tests were run frequently over the 10-hour seeding and sampling period. Table 79 gives the results of samplings taken at the beginning of the run, at a midpoint, and again at the conclusion. Some analyses were also performed on shipped samples by NERC Cincinnati. Where

TABLE 79. CHEMICAL-PHYSICAL ANALYTICAL RESULTS, VIRUS RUN NUMBER 1

TIME	5:00 AM		10:00 AM		3:00 PM	
	INFLUENT*	EFFLUENT*	INFLUENT*	EFFLUENT*	INFLUENT*	EFFLUENT*
Temp.° C	29	29	29	29	29	29
pH, units	7.1	6.8	7.1	6.7	7.1	6.9
Alk.as $CaCO_3$	124	120	126	110	124	110
Cond. umhos	740	766	874	908	738	772
D.O.	3.9	4.8	4.4	4.5	4.1	4.4
Hardness as $CaCO_3$	130	114	126	116	128	120
Color	50/40	50.35	50.40	30	50/40	40
Turb.FTU	8.5/11.0	2.0/2.5	9.0/11.0	1.7	9.3/12.0	2.5
COD	56/52	30/32	--/43	--	60/52	39
NH_3-N	0.4/0.4	0.1/0.8	0.0/0.1	0.0	0.0/<0.1	0.0
Org. N	4.3/3.8	2.7/1.1	4.1/2.4	2.4	4.9/3.7	2.7
NO_2+NO_3-N	4.0/4.9	3.5/3.7	4.0/4.6	3.5	5.0/5.9	5.0
SS	24/27	5/3	30/16	6	32/24	7
Total P	11.3/10.6	6.5/7.8	9.3/9.2	5.0	7.5/8.1	5.8

* Influent to and effluent from Densator

Denominator values are NERC analytical results on shipped samples.

Concentration in mg/l unless otherwise noted.

the time of those samples coincide with similar samples run by the Dallas staff, the NERC results are shown as a denominator value on the table.

Coliphage analyses on the three seeding containers showed:

Container 1	3.4×10^7 pfu/ml
Container 2	1.0×10^7 pfu/ml
Container 3	2.8×10^7pfu/ml
Average	2.4×10^7 pfu/ml

At the 100 ml/min seeding and 6.31 l/sec (100 gpm) flow, an average influent titer for the coliphage of 6360 pfu/ml should have been expected.

The results of the virus samplings are shown in Table 80 for coliphage and Table 81 for poliovirus. Influent and effluent analyses for both are depicted graphically in Figure 75. Calculated removals were 46 percent for coliphage and 63 percent for polioviruses. All virus samples from the chlorine contact basin were zero. Poliovirus analyses of the non-chlorinated sludge yielded 114 pfu/10 gm of sample. Chlorinated sludges were negative for both poliovirus and coliphage. However, the MPN tubes on the chlorinated sludge yielded positives for coliforms. Since virus analyses on the chlorinated sludges were negative, a mixing problem was suspected. The upflow clarifier was drained and a thick layer of sludge was found to exist under the fluidizer bar. Rubber scapers were then mounted on the bar and three air-lift pumps were installed to take the water from just above the fluidizer bar back to the mixing zone. Two test disinfection runs were performed and yielded no positive coliform tubes.

Virus Run Number Two

In the case of water treatment, it has been emphasized that coagulation and filtration are really one process and must be studied together (12). The same logic can be applied to wastewater in a reclamation operation. In preparing for the second run, therefore, some preliminary work was done to determine how to disinfect a mixed-media filter. It was decided to add calcium hypochlorite to the backwash water tank until a 40 mg/l free residual was achieved. This was then admitted to the filter and the filter allowed to soak overnight. The filter was then backwashed.

The upflow clarifier was still operating on an alum feed. For this run, the control parameter was not "Appearance", but rather the aluminum to phosphorus ratio. An effort was made to maintain the ratio in excess of 3.7:1 (20).

Much the same chemistry was run as in Virus Run Number One except that Table 82, showing the results at the beginning, mid-point, and end of run, also shows an entry for BOD_5. The same tests were run on the

TABLE 80. COLIPHAGE RESULTS, VIRUS RUN NUMBER ONE

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	160	156
6 AM	5240	600
7 AM	4000	640
8 AM	5400	460
9 AM	5500	3200
10 AM	5400	3000
11 AM	5600	2800
12 N	4800	3000
1 PM	6000	2600
2 PM	5800	3200
3 PM	2400	1800
Average last five hours	4920	2680

Percent removal: 46 Percent

TABLE 81. POLIOVIRUS RESULTS, VIRUS RUN NUMBER ONE

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	0	0
6 AM	510	11
7 AM	620	33
8 AM	550	36
9 AM	440	34
10 AM	400	52
11 AM	660	135
12 N	620	208
1 PM	590	289
2 PM	610	264
3 PM	500	192
Average	596	218

Percent removal: 63 Percent

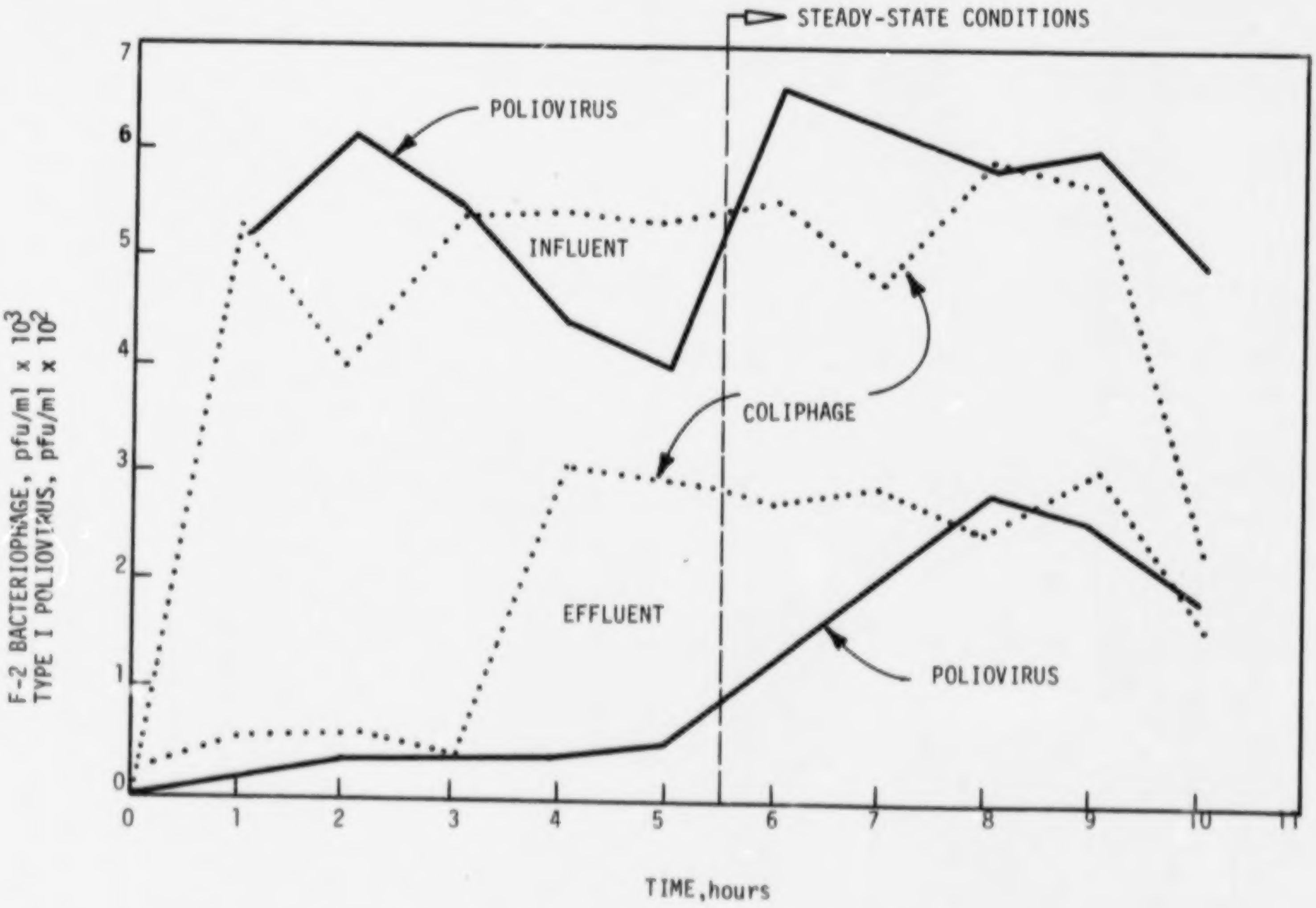

Figure 75. Influent and effluent virus counts obtained during Virus Run Number One.

TABLE 82. CHEMICAL-PHYSICAL ANALYTICAL RESULTS, VIRUS RUN NUMBER TWO

TIME	5:00 AM		10:00 AM		3:00 PM	
	INFLUENT*	EFFLUENT*	INFLUENT*	EFFLUENT*	INFLUENT*	EFFLUENT*
Temp. ° C	22	22	22	22	22	22
pH, units	7.1	6.5	7.3	7.2	7/4	6.7
Alk. as $CaCO_3$	145	60	170	110	175	110
Cond. umhos	574	649	597	658	629	686
D.O.	4.8	4.6	5.3	5.9	7.7	7.9
Hardness as $CaCO_3$	183	183	253	243	222	258
Color	40/22	15	30/27	10	30/13	10
Turb. **FTU	4.5/5.6	0.5(0.4)	3.5/5.5	0.6(0.4)	3.3/8.0	2.5(0.3)
COD	28.49	20	36/65	12	36/60	24
BOD_5	12	1	10	1	7	2
NH_3-N	0.3<.1	0.3	0.1<.1	0.3	0.1<.1	0.3
Org. N	2.4/2.7	1.5	2.5/3.1	1.7	2.4/3.1	1.5
NO_2+NO_3-N	5.0/6.0	3.5	6.5/5.6	6.0	7.0/7.6	6.0
SS*	12/7.5	5(3)	16/10	1 (2)	12/16	12 (3)
Total P **	3.5/3.9	0.2(0.2)	3.0/2.7	0.1(0.1)	3.0/2.9	0.3(0.1)

* Influent to and effluent from Densator

** Values in parentheses on filter effluent.

Denominator values are NERC analytical results on shipped samples.

Concentrations mg/l unless otherwise noted.

No. 1 mixed media filter effluent. The filter effluent results for turbidity, suspended solids, and total phosphorus are shown in parentheses. The Al:P ratio was 7:1, due primarily to unexpectedly low influent total phosphorus values.

The seeding technique for this run was similar to Virus Run Number One except that the 5-gallon Cubitainers were made up freshly before each use. Additionally, assays for both poliovirus and coliphage were conducted with the following results:

Container No.	Time of Use	Poliovirus pfu/ml	Coliphage pfu/ml
1	5:30 - 9:00	2.0×10^6	1.2×10^7
2	9:00 -12:35	2.3×10^6	1.4×10^7
3	12:35 - 3:00	2.3×10^6	1.0×10^7
Average		2.2×10^6	1.2×10^7

At the same 100 ml/min. seeding and 6.31 l/sec flow rates, an average influent titer of 580 pfu/ml poliovirus and 3170 pfu/ml coliphage should have been expected. Cooler weather prevailed during this run and the seeding containers were therefore not iced.

The results of the virus samplings for coliphage are shown in Table 83 and for polioviruses in Table 84. Figure 76 shows the influent titers graphically; effluent recoveries were too small to show on a similar scale. Calculated removals for coliphage were 99.845 percent on the upflow clarifier alone and 99.985 percent on coagulation plus filtration. No polioviruses were recovered on the effluents, and based on a sensitivity of assay of 0.5 pfu/ml, a greater-than 99.7 percent removal was calculated. Again, all virus samples from the chlorine contact basin were zero. Poliovirus titers on the non-chlorinated sludge yielded 223 pfu/gm of sample. Chlorinated sludges were negative for poliovirus, coliphage, and coliforms. Filter backwash water was similarly negative.

Virus Run Number Three

In order to get as high a titer as possible, some staff members wanted to slug dose the upflow clarifier with the two viruses. Others, who were more acute to the relatively higher pH-resistance of the polioviruses, opted for the same type of seeding technique used in the alum studies. A compromise was effected in which it was agreed to add the viruses in a steady stream over about a five-minute period. Samples of the seeded influent were taken midway through the seeding with the following results:

TABLE 83. COLIPHAGE RESULTS, VIRUS RUN NUMBER TWO

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml	FILTERED pfu/ml
BACKGROUND	54	0	0
1	3200	0	0
2	2800	0	0
3	2400	0	0
4	3600	2	0
5	3400	2	0
6	2800	4	0
7	2700	4	0
8	2600	6	0
9	2200	6	2
10	2600	0	0
Average last five hours	2580	4	0.4

Percent removal:

Densator: 99.845

Densator plus filter: 99.985

TABLE 84. POLIOVIRUS RESULTS,VIRUS RUN NUMBER TWO

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml	FILTERED pfu/ml
BACKGROUND	0	--	--
1	110	0	0
2	118	0	0
3	156	0	0
4	109	0	0
5	109	0	0
6	132	0	0
7	108	0	0
8	101	0	0
9	86	0	0
10	139	0	0
Average last five hours	113	0	0

(Sensitivity of assay = 0.5 pfu/ml)

Percent removal: > 99.7

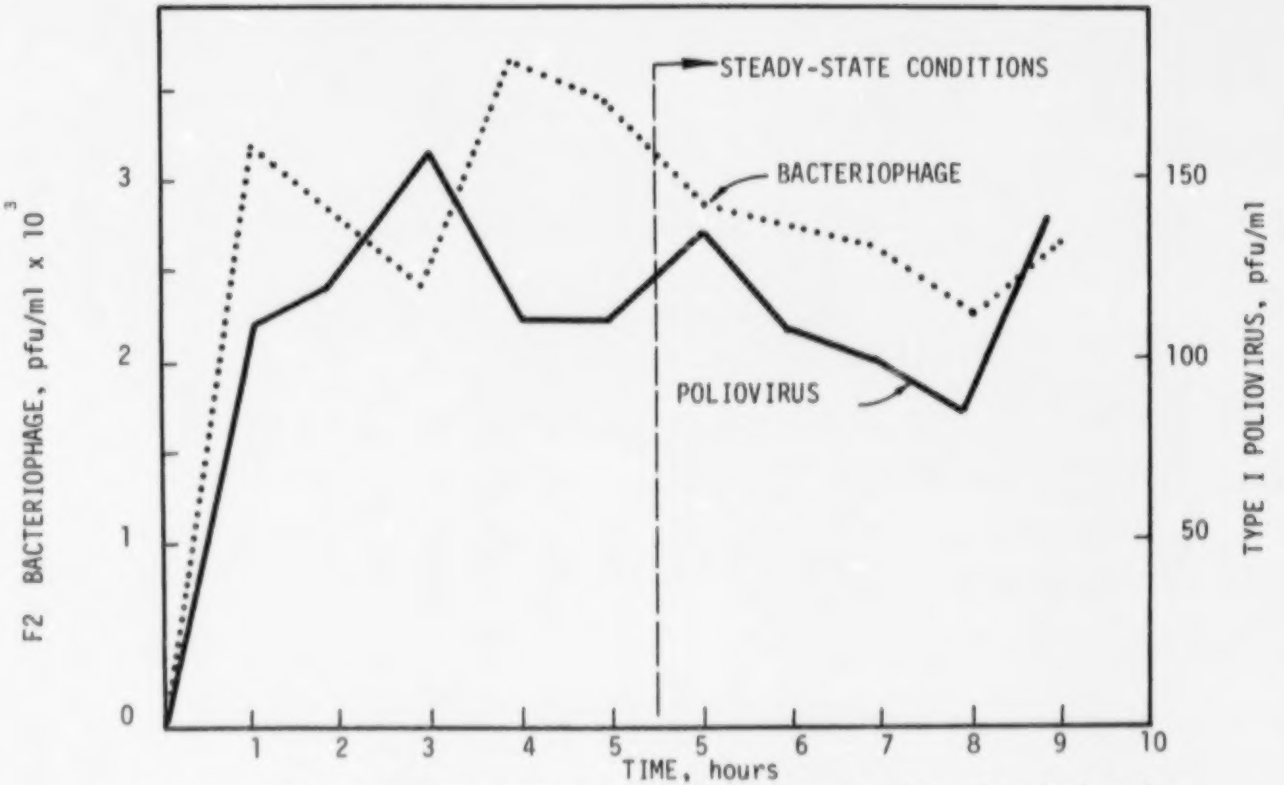

Figure 76. Influent virus counts obtained during Virus Run Number Two.

TABLE 85. CHEMICAL-PHYSICAL ANALYTICAL RESULTS, VIRUS RUN NUMBER THREE

TIME	5:15 AM		10:15 AM		3:15 AM	
	INFLUENT[1]	EFFLUENT[2]	INFLUENT[1]	EFFLUENT[2]	INFLUENT[1]	EFFLUENT[2]
Temp° C	20	20	19	19	19	19
pH[3], units	7.0	11.8-6.3	7.5	11.9-9.6	7.2	11.7-8.3
Alk. as $CaCO_3$	150	195	142	152	136	332
Cond. umhos	745	833	778	800	760	980
Color	40/20	0/11	50	0	50	5
Turb. FTU	11.0/14	1.5/6.4	8.0	2.2	8.5	1.0
COD	40/34	28/15	481	28	48	16
NH_3-N	0.0/0.2	0.0/0.1	0.0	0.0	0.0	0.0
Org. N	2.7/2.2	1.0/0.8	2.7	1.3	3.4	1.8
NO_2+NO_3-N	12.0/10.7	9.0/10.4	11.5	5.0	12.5	11.5
SS	20/14	11/19	32	142	32	61
Total P	6.5/4.9	0.26/0.3	7.5	0.2	7.5	0.33

[1] Influent to Densator

[2] Effluent from Recarbonation

[3] Effluent pH values before and after recarbonation

Denominator values are NERC analytical results on shipped samples

Concentration in mg/l unless otherwise noted.

TABLE 86. COLIPHAGE RESULTS, VIRUS RUN NUMBER THREE

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	89	
Seeding (4 min. 20 secs. 4400 mls mixed viruses)	7.2×10^5	
All effluent samples (Taken each 30 minutes for 10 hours)		0
Stock titer:	7.2×10^7 pfu/ml	

TABLE 87. POLIOVIRUS RESULTS, VIRUS RUN NUMBER THREE

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	0	
Seeding (4 min. 20 secs., 4400 mls mixed viruses)	8×10^4	
All effluent samples (Taken each 30 minutes for 10 hours)		0
Stock titer:	7.0×10^7 pfu/ml	

TABLE 88. REGROWTH STUDY RESULTS

	DENSATOR EFFLUENT			RECARBONATION EFFLUENT			RECARBONATED PLUS 24 HOURS	
Sample Date	PH	Total Count per ml	% Gm-	PH	Total Count per ml	% Gm-	Total Count per ml	% Gm-
12/12/73	12.0	2	0	7.4	5	5	4	0
12/13/73	11.8	11	0	7.2	24	--	>1000	--
12/14/73	10.4	150	0	6.4	230	50	TNTC	--
12/15/73	11.4	26	0	7.0	64	60	19,500	75
12/16/73	11.3	28	0	6.8	93	60	348	70
12/17/73	11.3	61	0	7.5	268	60	>1000	--

Coliphage Titer 7.2×10^7 pfu/ml

Poliovirus Titer 8.0×10^4 pfu/ml

The Densator was operated on a lime feed calculated as 391 mg/l as CaO and a supplemental feed of 18.6 mg/l ferric chloride as Fe. The results of the chemical analyses at three different times during this run are shown in Table 85. The effluent samples were taken after recarbonation -- as were the virus samples. The results of the virus analyses are shown in Tables 86 and 87 ; all effluent samples (one sample for each virus every 30 minutes over a 10-hour period following the seeding) were zero. The results of all the control samples on the terminal chlorination process and on the sludges were also zero. In this high-pH lime run, the Densator itself was not terminally chlorinated. Instead, the unit was isolated and the sludges allowed to mix for a number of days until results of the poliovirus assay were received from Cincinnati indicating there were no polioviruses left.

Although plant control, especially with the recarbonation process, was not as good as desired, the virus results obtained substantiated earlier observations of effectiveness against coliphage f2. At this point in time a new problem developed. Routine bacterial tests for total coliforms, fecal coliforms and total plate counts were showing a possible regrowth of these organisms in the recarbonated effluent (see Table 88). In another check of regrowth, a one-liter grab sample of Densator effluent was taken to the lab and a six-replicate total plant count was performed. The sample was recarbonated using aseptic technique and another six-plate count was made. Lastly, the sample was held at room temperature for 24 hours and a third six-plate count run. The results are shown in Table 89.

TABLE 89. LABORATORY RECARBONATION AND REGROWTH STUDY RESULTS

SAMPLE	pH	Total Count/ml Avg. of 6 plates	Range of Counts
Densator Effluent	11.1	11.2	5-20
Recarbonated	6.8	10.5	6-17
24 Hours	6.6	6,000	5700-7400

Virus Run Number Four

The fourth and last virus run duplicated Virus Run Number Three except for some slight changes. Better control over recarbonation was effected. Quicker feeding of the seed virus was accomplished. Soluble TOC's were performed rather than COD's. Finally, virus sampling was limited to 14 samples collected over an 8-hour period (0, ½, 1½, 2,2½, 3, 3½, 4, 4½, 5, 5½, 6, 7, and 8 hours after seeding) instead of every half hour over a 10-hour period. Samples of the seeded influent water coming to the Densator taken half-way through the seeding showed the following titers:

Coliphage Titer	2×10^4 pfu/ml
Poliovirus Titer	4×10^4 pfu/ml

Chemicals used in the Densator for this run were 383 mg/l lime as CaO and 9.3 mg/l of $Fe(Cl)_3$ as Fe. The results of the chemical analyses at three different times during the run are shown in Table 90. The results of the virus samplings are shown in Tables 91 and 92. All effluent samples were zero. The results of all the chlorination controls were again zero. Samples of sludge were taken 1, 2, and 3 hours after the seeding and again 24 hours later. No polioviruses were found in any of these samples. The 1-and 2-hour samples were not run for coliphage but the 3-hour and 24-hour samples were. One-half ml of the 3-hour sample plated directly as if it were water yielded 9 plaques. The 24-hour sample was plated directly and also blended, centrifuged in a clinical centrifuge, and the supernatant plated; both yielded no coliphages. Since the pipe and tap from which the sludge samples were collected could not be sterilized, the integrity of the samples are questionable. Thus, negative assays would be meaningful but positive samples could hardly be conclusive.

Summary

The rather large-scale pilot-studies conducted herein demonstrated that virus removals from secondary effluents by alum coagulation-sedimentation and coagulation-sedimentation-filtration processes are essentially as described in the literature using smaller scale processes. Removal of bacterial virus as high as 99.845 percent for coagulation-sedimentation and 99.985 percent for coagulation-sedimentation-filtration processes were observed at an Al:P ratio of 7:1.

A marked decrease in virus removals was observed at a lower alum dose. At an Al:P ratio of 0.44:1, removals of only 46 percent of f2 coliphage and 63 percent of poliovirus by the coagulation-sedimentation process *per se* were observed.

High-pH treatment of secondary effluents achieved very high degrees of virus removal.

Bacteriological tests (total plate count procedure) of the recarbonation process (used for pH neutralization) indicate that some bacteria which gain entry to this process can reproduce in the recarbonation basin. However, no viruses were found in the recarbonated effluents.

Since the viruses that were added in these tests were probably not imbedded in particulates that could protect them from the adverse high-pH environment, these results must be interpreted with caution.

TABLE 90. CHEMICAL-PHYSICAL ANALYTICAL RESULTS, VIRUS RUN NUMBER FOUR

TIME	3:00 AM		7:00 AM		11:00 AM	
	INFLUENT[1]	EFFLUENT[2]	INFLUENT[1]	EFFLUENT[2]	INFLUENT[1]	EFFLUENT[2]
Temp °C	18	19	18	18	18	18
pH [3],units	7.0	11.0-6.0	7.2	11.0-6.5	7.1	11.3-6.1
Alk. as $CaCO_3$	135	400	135	435	135	450
Cond. umhos	864	1190	828	1260	824	1270
Hardness as $CaCO_3$	156	389	133	403	151	415
Color	45.52	15/14	35	15	35	15
Turb.	3.8/4.6	1.5/3.2	4.0	1.5	4.5	2.0
COD	34/35	21/27	29	17	21	8
TOC	9/11.4	9/9.8	11	6	11	0
sol NH_3-N	0.07 <0.1	0.15/0.2	0.14	0.13	0.04	0.11
Org. N	3.35/2.3	1.67/1.9	2.70	1.61	2.80	1.99
NO_2+NO_3-N	9.5/9.7	11.5/8.2	8.5	10.5	8.5	10.0
SS	2/10	1/7	4	0	4	8
Total P	10.3/10.3	0.5/0.2	10.3	0.4	10.3	0.5

[1] Influent to Densator

[2] Effluent from Recarbonation

[3] Effluent pH value before and after recarbonation

Denominator values are NERC analytical results on shipped samples.

Concentration in mg/l unless otherwise noted.

TABLE 91. COLIPHAGE RESULTS, VIRUS RUN NUMBER FOUR

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	28	
Seeding (4 min., 6 secs. 4000 mls mixed viruses)	2×10^4	
All effluent samples (14 samples collected over 8-hour period)		0
Stock titer:	9.3×10^7 pfu/ml	

TABLE 92. POLIOVIRUS RESULTS, VIRUS RUN NUMBER FOUR

SAMPLE	INFLUENT pfu/ml	EFFLUENT pfu/ml
BACKGROUND	0	
Seeding (4 min., 6 secs. 4000 mls mixed viruses)	4×10^4	
All effluent samples (14 samples over 8-hour period)		0
Stock titer:	5.7×10^7 pfu/ml	